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PRELIMINARY STUDY OF COMPUTER MODELING OF THE DYNAMIC FUEL CONDITIONS IN WEAPON SYSTEM VULNERABILITY ANALYSIS

FINAL REPORT

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FOREWORD

This report summarizes the results of a study performed by Caywood-Schiller Division of A.T. Kearney, Inc. under U.S. Air Force Contract F33615-73-C-2078. The work was conducted between 1 July 1973 and 31 March 1974, under the direction of the Air Force Aero Propulsion Laboratory, with Mr. G. W. Gandee (AFAPL/SFH) acting as Project Engineer.

Work was sponsored by JTCG/AS as part of the 3-year TEAS (Test and Evaluation, Aircraft Survivability) program. The TEAS program was funded by DDR&E/ODDT&E. The effort was conducted under the direction of the JTCG/AS Vulnerability Assessment Subgroup, as part of TEAS element 5.1.6.6, *Development of Models for Assessment of the Vulnerability of Aircraft Fuel Systems.*

A study was conducted to develop a dynamic model of the vulnerability of an aircraft fuel system to threats posed by hostile weapons. Improvement was achieved in treating fuel system vulnerability. Further development of the fuel system model is recommended.

DISCLAIMER

Estimates in this report are not to be construed as an official position of any of the Services or of the Joint AMC/NMC/AFLC/AFSC Commanders.

NOTE

Information and data contained in this document are based on reports available at the time of preparation, and the results may be subject to change.

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Air Force Aero Propulsion Laboratory
Preliminary Study of Computer Modeling of the Dynamic Fuel Conditions in Weapon System Vulnerability Analysis, by M.A. Dloogatch, W.R. Doane, and P.C. Hewett, Caywood-Schiller Division of A.T. Kearney, Inc. Wright-Patterson Air Force Base, OH, AFAPL, for Joint Technical Coordinating Group/ Aircraft Survivability, September 1976, 62 pp. (Report JTCG/AS-74-V-011, publication UNCLASSIFIED.)

This report presents the results of a study to develop a dynamic model of the vulnerability of an aircraft fuel system to the threats posed by hostile weapons. A Monte Carlo model was developed to calculate the probability of hit along segments of a specified flight profile at each point where a specified weapon system could pose a threat to the fuel system. An Air Force developed computer model (Well-Stirred Fuel Tank Model) is used to compute fuel state in each fuel tank under study at increments along the flight path. These are used as inputs to the Monte Carlo model.

Given that a hit takes place, the probable trajectories (liquid-air, liquid-liquid, and air-air) are calculated, and the probabilities of lethal outcomes (explosion, internal fire, external fire, leak) are computed. The model ranks the most likely events, and a hazard index is generated which portrays the most important threats to the fuel system on the specified flight path.

The resulting model gives an improved measure of the impact of fuel state on the vulnerability of a fuel system on aircraft vulnerability. It does not incorporate consideration of the effects of fuel slosh, vibration, or vent geometry. Further refinement and development is recommended.

CONTENTS

INTRODUCTION

PURPOSE

This report presents the results of an exploratory study to develop a dynamic representation of the vulnerability of an aircraft fuel system to hostile threats.

BACKGROUND

Some analytical studies use gross aggregation in representing the vulnerability of an aircraft fuel system. Typically, a fixed percentage of fuel is assumed, empty and external fuel tanks ignored, and the wide variation in probability of a reaction within the various kinds of fuel tanks is compressed to a single probability of fire given a hit. Also, distinction in hazard between liquid fuel and tank ullages, influence of tank wall and liquid temperatures on the ullage composition, tank overpressure caused by internal fires, and effect of venting are largely ignored. Analyses conducted under these simplifying assumptions are valid, and study results are reliable and important; but more precise representation is required for test planning, fuel system design, and detailed examination of the fuel system vulnerability area. The greater accuracy of a dynamic fuel system vulnerability model will be beneficial in future aircraft development studies because delineation of specific vulnerabilities and more precise measurement of previously identified vulnerability will be possible

In performing this background study, the WSFT (Well-Stirred Fuel Tank) computer program, developed for the Air Force by Dynamic Science, Inc., was considered the most accurate representation of internal fuel state. The WSFT program does not consider the hostile threats; therefore, a vulnerability model was constructed to combine the WSFT program fuel states with anticipated threats.

WSFT PROGRAM

GENERAL

The WSFT program, which is an integral part of the fuel vulnerability model, was developed under a prior AFAPL study[1]. The program determines the fuel-to-air ratio in the ullage space of a fuel tank as a function of time for a particular input mission profile and describes the state of fuel and vapor space in fuel tanks, accounting for mass and energy transport due to:

(1) fuel evaporation

(2) venting effects

(3) heat transfer between ullage, tank walls, and liquids

(4) outgassing as dissolved air is removed from the liquid as the aircraft climbs.

The program does not consider interaction of a fuel tank and an ignition source, such as in an incendiary projectile. The fuel vulnerability model developed in this study combined the interaction of threat and fuel tank.

[1] Air Force Aero Propulsion Laboratory. *Analysis of Aircraft Fuel Tank Fire and Explosion Hazard*, by T.C. Kosvic, L.B. Zung, M. Gerstein. Wright-Patterson Air Force Base, OH, AFAPL, March 1971. 75 pp. (AFAPL-TR-71-7, publication UNCLASSIFIED.)

INPUTS REQUIRED

Basic inputs required by the WSFT program are:

1. Altitude profile of aircraft
2. Liquid temperature history
3. Skin and structure temperature
4. Vapor pressure relations of liquid fuels
5. Ullage volume and exposed surface area schedule
6. Vent size
7. Internal heat transfer coefficients between ullage and tank structure.

Standard FORTRAN IV NAMELIST is used for all input data to the WSFT program. The variable list and definitions for the input data under the NAMELIST name DATA are presented in Table 1. An example of a set of inputs to the program is provided in Figure 1.

OUTPUT

The normal output of the WSFT program is a report for each print time throughout the mission profile. Each report describes the state of the fuel and vapor space at that particular time in terms of air and fuel partial pressures, fuel vapor pressure, fuel-to-air ratio, and mass and mass flux of fuel vapor that has been vented, evaporated, outgassed, or condensed. In addition to these parameters, the altitude, speed, and amount of fuel used are printed out. An example of the printout of this report is shown in Figure 2. The WSFT output parameters used for the vulnerability model were the fuel-to-air ratio and the amount of fuel used as a function of time. Tables of fuel-to-air ratios and the percent of fuel remaining in each tank as a function of time were generated. These tables were stored on magnetic tape and used as input to the fuel vulnerability model.

INHERENT ASSUMPTIONS AND LIMITATIONS

The WSFT program assumes a homogenous mixture of fuel vapor and air. The mixing of air and vapor is assumed to occur rapidly with no appreciable difference in fuel-to-air ratio within the ullage volume. The program is particularly applicable for shallow tanks or tanks where the ratio of ullage volume to liquid fuel surface is small. It was considered beyond the scope of this study to develop a new model which would incorporate the concept of a stratified ullage space of different fuel-to-air ratios.

The effects of vibration and slosh on the fuel-to-air ratio are not included in the WSFT program. One of the inputs required is the liquid temperature history of the fuel in the tank. This information must be provided by the user; it is important because aerodynamic heating or cooling may have a significant influence on the temperature of the fuel and heat sources within the aircraft. These factors should be considered in the development of more sophisticated models for determining fuel-to-air ratios.

Table 1. Variable Names and Definitions.

Name		Definition	Units
SDATA		Ident of data block	
RGAS		Universal gas constant	ft-lbm/lb-mole °R
EMWA		Mass of air	lbm/lbm-mole
EMWF		Mass of fuel	lbm/lbm-mole
CPA		Specific heat of air	BTU/lbm °R
CPF		Specific heat of fuel	BTU/lbm °R
TA		Temperature of the ullage	°F
HJ(J)		H_j heat transfer film coefficient	BTU/ft^2 hr °R
		J=1, to fuel surface	
		J=2, to side of tank	
		J=3, to top of tank	
ZOG	1	Set equal to one	None
DV		Diffusion coefficient	ft^2/hr
CDELTA		Characteristic length for evaporation	ft
KTANK	0	Set equal to zero	None
GALO		Initial volume of fuel	gal
BETA		Bunsen coefficient	
CON1		Outgassing coefficient	hr^{-1}
CON2		Solution coefficient	hr^{-1}
TVENT		If TVENT=0, incoming air will be calculated from altitude and Mach number schedule	°F
		If TVENT≠0, all incoming air will have temperature=TVENT	
TF(1,1)		Table of time values corresponding to fuel temperature table	hrs

Table 1. Variable Names and Definitions (Continued).

Name	Definition	Units
TF(1,2)	Table of fuel temperatures at times corresponding to TF(1,1)	°F
TSIDE(1,1)	Table of time values corresponding to tank side temperature table	hrs
TSIDE(1,2)	Table of tank side temperatures at times corresponding to TSIDE(1,1)	°F
TTOP(1,1) TTOP(1,2)	Same as TSIDE except applies to top of the tank	
ALT(1,1)	Table of times corresponding to altitude schedule table	hrs
ALT(1,2)	Table of altitudes at times corresponding to ALT(1,1)	KFT
GALDOT(1,1)	Table of time values corresponding to fuel usage	hrs
GALDOT(1,2)	Table of fuel usage at times corresponding to GALDOT(1,1)	gal/hr
EMINF(1,1)	Table of time values corresponding to flight Mach number schedule	hrs
EMINF(1,2)	Table of flight Mach numbers at times corresponding to EMINF(1,1)	None
PVAP(1,1)	Table of temperatures corresponding to fuel vapor pressure	°F
PVAP(1,2)	Table of fuel vapor pressure corresponding to PVAP(1,1)	psia
TO	Initial time for start of integration	hrs
TMAX	Final integration time	hrs
DT	Time step for integration	hrs
DTPRNT	Print time interval	hrs
AV	Area of the vent	ft^2
DELHF	Heat of formation of fuel	BTU/lbm

Table 1. Variable Names and Definitions (Continued).

Name	Definition	Units
ULLGH	Ullage length	ft
ULWID	Ullage width	ft
ULHT	Ullage height	ft
$	End	

```
$DATA
RGAS=1545,
EMWA=28.966,EMWF=72,
CPA=0.24,CPF=0.49,
TA=60,
HJ=3*2,
ULLGH=10.0,ULWID=10.0,ULHT=0.55,
DELHF=1,
ZOG=1,
AV=0.16,
DV=0.3,
CDELTA=0.01,
KTANK=0,
GALO=5573,
BETA=0.16,
CON1=1000,CON2=0,
TVENT=70,
TF(1,1)=0,1,2,3,4,5,6,7,8,9,10,11,12,
TF(1,2)=60,60,58,48,48,45,15,18,20,25,110,130,120,
TSIDE(1,1)=0,12,TSIDE(1,2)=70,70,
TTOP(1,1)=0,12,TTOP(1,2)=70,70,
ALT(1,1)=0,.1,.3,.5,1,4,5,6,8,8.3,12,
ALT(1,2)=0,8,20,22,22,20,18,20,22,.25,.25,
GALDOT(1,1)=0,8.3,8.31,10.3,10.31,12,
GALDOT(1,2)=0,0,2779,2779,0,0,
PVAP(1,1)=17,41,67,96,129,166,PVAP(1,2)=.35,.60,1.1.2.0,4.0,8.0,
EMINF(1,1)=0,.5,12 ,EMINF(1,2)=0,.85,.85,
TO=0,TMAX=11,DTPRNT=.25,DT=.001$
```

*A header card must be present for each run on the WSFT program. The subsequent data cards contain the variable names and corresponding values required by the model. The data is punched on cards beginning in column two.

Figure 1. Example of a Set of Inputs for WSFT Program.

Time hrs	= 1.7500	Air partial pressure	= .77882E+03
Mach number	= .85000	Fuel partial pressure	= .13494E+03
Vent velocity	= 1.6085 (ft/hr) (positive into tank)	Fuel vapor pressure	= .13486E+03
Integration error total mass-percent	= -1.6841	Air-fuel ratio	= .23219E+01

	Value	Derivative
Altitude	.21500E+05 (ft)	-.66667E+03 (ft/hr)
Pressure	.91376E+03 (psf)	.25775E+02 (psf/hr)
Temperature	.52590E+03 (°R)	-.91200E+00 (°R/hr)
Volume	.5500E+02 (ft^3)	0. (ft^3/hr)
Gallons used	0.	0. (gal/hr)

	Mass, slugs	Mass flux, slugs/hr
Vented	-.99572E+01	.62984E-01
Evaporated	.19764E+01	-.25420E-01
Outgassed	.55206E+01	0.
Condensed	0.	0.
Total	.21486E+01	.37564E-01

Figure 2. Example of WSFT Program Normal Output Report.

VULNERABILITY MODEL

UTILITY

The vulnerability model was designed to ascertain the most hazardous phases of a designated flight profile, given a specific aircraft and a specified set of hostile weapons. It is intended for use in support of laboratory testing, both to reduce the number of tests required and to eliminate unnecessary tests.

INPUTS

To prepare for model runs, it is necessary to have input information in several categories (i.e., mission, weapons, and aircraft). See the Appendix for program listing and sample case.

In addition to the input from the WSFT program, the vulnerability model requires input information regarding ignition and detonation probabilities as functions of residual penetrator energy, and hydraulic ram probability as a function of impact kinetic energy. It also requires a geometric description of the fuel system and the hostile weapons under consideration.

Mission

The flight profile must be selected; which includes altitude, velocity, and time of the target aircraft during the period when hostile weapons may be expected.

Weapons

The model will accept any mixture of kinetic energy penetrators or fragmenting warhead weapons in a sector of attack determined by a range of permissible azimuth and elevation angles for each hostile weapon system.

KINETIC ENERGY WEAPONS. The parameters which characterize the kinetic energy penetrators (e.g., ball, AP*, and API*) are: mass of the penetrator, time of incendiary ignition and incendiary burnout (relative to initial contact), muzzle velocity, drag coefficient, and a table of mil aiming errors as a function of target velocity. For each shot, the azimuth and elevation angles are taken from uniform distributions within the prescribed limits for the firing weapon system. The probable aiming error is calculated from the table of mil errors. A particular D_M (miss distance) is chosen from a normal distribution characterized by this probable error. A point is chosen at random on the circumference of a circle having a radius equal to the D_M and lying in the plane perpendicular to the relative velocity vector. This point and the relative velocity vector determine the trajectory. If the trajectory intersects any of the fuel tanks, a hit is said to occur on that tank. If a hit takes place, the geometry of the situation and the conditions within the fuel tank determine whether a particular damage mechanism occurs.

*Armor-piercing and armor-piercing incendiary.

FRAGMENTING WARHEAD WEAPONS. The parameters which characterize the fragmenting warhead weapons are: (1) average fragment mass, (2) fragment static emission velocity, (3) fragment slowdown constant, (4) static fragment spray limits, (5) average static fragment density/steradian, (6) muzzle velocity of projectile, (7) slowdown constant of projectile, (8) aiming sigma, and (9) fuzing sigma. For each shot, a trajectory is chosen as with the solid shot weapons, using the aiming sigma in place of the table of mil errors. A burst point is chosen along the trajectory from a normal distribution using the fuzing sigma. For each fuel tank, the travel-time equation of the fragments is solved using an iterative procedure. The expected number of hits on each tank is calculated; this number and the conditions in the tank determine the probability of a particular damage mechanism.

Aircraft

The target aircraft is represented as a set of fuel tanks. Each tank is a rectangular parallelepiped characterized by the coordinates of its center, and by its length, width, and height. Constants, which must be supplied by the user, are stored; they represent, for the aspect of each tank, whether an external ignition source is present, and the distance of that aspect from the skin of the aircraft. The target is further characterized by the target velocity and by the energy levels required to produce penetration of each fuel tank and hydraulic ram effects.

PROGRAM OUTPUT

There are two reports generated by the program. Report 1 is a summary of fuel states for each tank as a function of time. (See Table 2). Report 2 is a summary of each non-zero hazard incident. (See Table 3.) It shows the fuel state at the time of the incident, summarizes the probable trajectories through the tank if impact occurs, and presents probabilities of no effect, leak, external fire, destructive ram, and internal fire/explosion. These probabilities are calculated as the average over several Monte Carlo trials for each combination of fuel tank, weapon, and time intervals resulting in a non-zero P_H (probability of a hit) on the fuel tank. A summary of all Report 2 outputs is made, arranging hazards in descending order.

For solid shot weapons, the probabilities of liquid and vapor exit are given. On the basis of all these probabilities, a hazard index is calculated; which indicates, on a scale of zero through one, the relative likelihood of lethal damage occurring to the aircraft as a result of this encounter.

COORDINATE SYSTEM AND AZIMUTH-ELEVATION CONVENTION

The coordinate system used in this model has its origin at the center of gravity of the target aircraft; therefore, it is a moving coordinate system. The X axis is positive in the direction of travel. (See Figure 3.) The Y axis is positive in the direction of the left wing, and the Z axis is positive in an upward direction.

In the analysis, the orientation of certain vectors with respect to certain axes is sometimes expressed in terms of direction cosines and in terms of azimuth-elevation; thus, conversion between these terms is required. The sign convention for azimuth-elevation needs definition because all users do not use identical conventions.

Table 2. Fuel Tank Vulnerability Model (Report 1).

Vehicle - Test

	TANK 1		TANK 2							
TIME INTO MISSION	F/A RATIO	PCT. FUEL REMAINING	F/A RATIO	PCT. FUEL REMAINING	F/A RATIO	PCT. FUEL REMAINING	F/A RATIO	PCT. FUEL REMAINING	F/A RATIO	PCT. FUEL REMAINING
0.000	.174764	100.00	.174764	100.00						
.250	.310226	100.00	.310431	100.00						
.500	.444017	100.00	.444072	100.00						
.750	.457327	100.00	.457327	100.00						
1.000	.457327	100.00	.457327	100.00						
1.250	.448503	100.00	.448495	100.00						
1.500	.439516	100.00	.439510	100.00						
1.750	.430690	100.00	.430684	100.00						
2.000	.422020	100.00	.422014	100.00						
2.250	.394664	100.00	.394632	100.00						
2.500	.366976	100.00	.366947	100.00						
2.750	.340186	100.00	.340157	100.00						
3.000	.314242	100.00	.314213	100.00						
3.250	.310331	100.00	.310332	100.00						
3.500	.307901	100.00	.307901	100.00						
3.750	.305495	100.00	.305495	100.00						
4.000	.303113	100.00	.303113	100.00						
4.250	.290022	100.00	.290013	100.00						
4.500	.277086	100.00	.277079	100.00						
4.750	.264677	100.00	.264669	100.00						
5.000	.252776	100.00	.252768	100.00						
5 250	.213226	100.00	.213191	100.00						
5.500	.185938	100.00	.185901	100.00						
5.750	.157974	100.00	.157935	100.00						
6.000	.135357	100.00	.135362	100.00						
6.250	.137144	100.00	.137146	100.00						
6.500	.138670	100.00	.138672	100.00						
6.750	.141078	100.00	.141084	100.00						
7.000	.146006	100.00	.146013	100.00						
7.250	.149995	100.00	.150000	100.00						
7.500	.153982	100.00	.153988	100.00						
7.750	.158052	100.00	.158058	100.00						
8.000	.162207	100.00	.162213	100.00						
8.250	.079088	100.00	.079093	100.00						
8.500	.071342	100.00	.063685	90.30						
8.750	.073696	100.00	.065436	77.83						
9.000	.076055	100.00	.067344	65.37						
9.250	.119225	100.00	.086189	52.90						
9.500	.199056	100.00	.139000	40.44						
9.750	.334348	100.00	.217422	27.97						
10.000	.579576	100.00	.330200	15.50						
10.250	.522805	85.05	.486403	3.04						
10.500	.565363	60.05	.637119	.27						
10.750	.653889	35.05	.751950	.27						
11.000	.735050	10.05	.855327	.27						

Table 3. Fuel Tank Vulnerability Model (Report 2).

Solid Shot Weapon

TIME INTO MISSION (HRS) – 10.000
PROBABILITY OF HIT ON FUEL TANK – .030000
AVERAGE STRIKING VELOCITY (FPS) – 2569.2
AVERAGE SLANT RANGE (FT) – 497.6
AIRCRAFT ALTITUDE (FT) – 250.00
AIRCRAFT SPEED (FPS) – 948.5

VEHICLE – Test
FUEL TANK – AFT INTERMEDIATE
THREAT – RP-46
PERCENT FUEL REMAINING – 100.00
FUEL TEMPERATURE (F) – 110.00
FUEL/AIR RATIO – .579576

PROBABILITY OF LIQUID ENTRY – 1.000000
GIVEN LIQUID ENTRY –
  PROBABILITY OF LIQUID EXIT – .333333
  PROBABILITY OF VAPOR EXIT – .666667

PROBABILITY OF VAPOR ENTRY – 0.000000
GIVEN VAPOR ENTRY –
  PROBABILITY OF LIQUID EXIT – 1.000000
  PROBABILITY OF VAPOR EXIT – 0.000000

PROBABILITIES OF FUEL TANK DAMAGE
GIVEN A HIT

P (NO EFFECT)	= .000000
P (LEAK WITHOUT FIRE	= .666667
P (LEAK AND EXTERNAL FIRE)	= .333333
P (DESTRUCTIVE RAM)	= 0.000000
P (INTERNAL FIRE/EXPLOSION)	= 0.000000

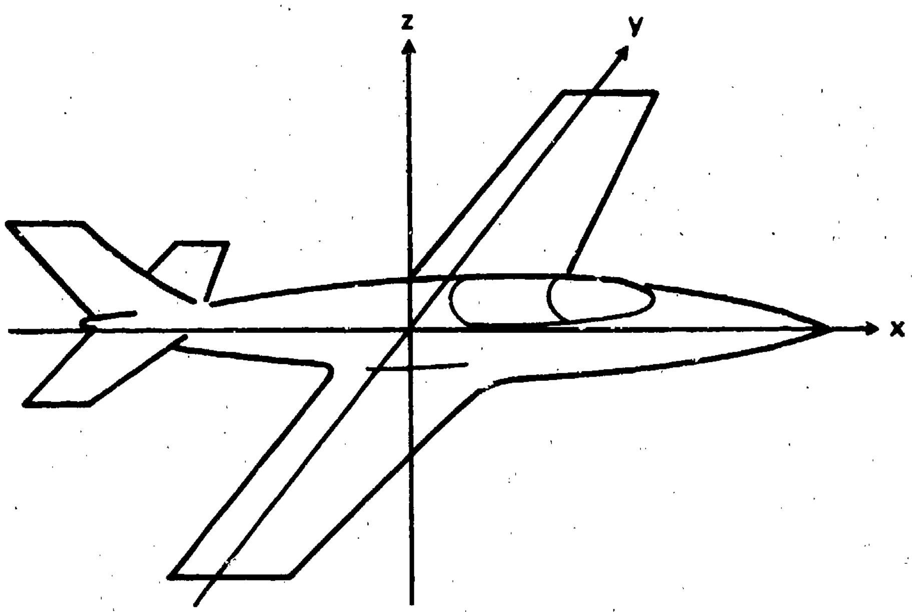

Figure 3. Moving Coordinate System.

Consider the X, Y. and Z axes and the $\vec{V}_{SH}$ (shell velocity) having direction cosines μ_X, μ_Y, and μ_Z. The El (elevation angle) is the angle between the vector and the XY plane. It is considered positive if the vector has an upward component, and negative if it has a downward component. The Az (azimuth angle) is the angle between the projection of the vector on the XY plane and the negative X axis. It is considered positive if the vector has a component in the -Y direction.

The relations between the direction cosines and azimuth-elevation can be derived by resolving the unit $\vec{V}_{SH}$ into its components along the coordinate axes. The magnitude of the Z axis component is $|\sin El|$, while the projection in the XY plane is $|\cos El|$. The latter component may be projected on the X axis to yield cos El cos Az and on the Y axis to yield $|\cos El \sin Az|$. Thus, the unit vector has components along the X, Y, and Z axes whose magnitudes are $|\cos El \cos Az|$, $|\cos El \sin Az|$, and $|\sin El|$. Taking the sign conventions into account:

$$\mu_X = -\cos El \cos Az \tag{1}$$

$$\mu_Y = -\cos El \sin Az \tag{2}$$

$$\mu_Z = \sin El \tag{3}$$

These equations permit calculation of the direction cosines if Az and El are given.

TRAJECTORY

For a single shot, it is assumed that Az and El are uniformly distributed between the limits Az_{MIN}, Az_{MAX}, El_{MIN}, and El_{MAX}. El is found by selecting an r_u (random number) uniformly distributed between zero and one and using it in:

$$El = El_{MIN} + r_u(El_{MAX} - El_{MIN}) \tag{4}$$

Az is found by selecting another r_u for use:

$$Az = Az_{MIN} + r_u(Az_{MAX} - Az_{MIN}) \tag{5}$$

The direction cosines μ_X, μ_Y, and μ_Z can be calculated from equations (1), (2), and (3).

The $\vec{V}_{SH}$ has magnitude V_{SH} and is expressed in equation (6), where $\vec{i}$, $\vec{j}$, and $\vec{k}$ represent the unit vectors in the X, Y, and Z directions, respectively. The $\vec{V}_T$ (target velocity) has magnitude V_T, is in the X direction, and appears in equation (7):

$$\vec{V}_{SH} = V_{SH}\,\mu_X\,\vec{i} + V_{SH}\,\mu_Y\,\vec{j} + V_{SH}\,\mu_Z\,\vec{k} \tag{6}$$

$$\vec{V}_T = V_T\,\vec{i} \tag{7}$$

The $\vec{V}_R$ (relative velocity) has magnitude V_R, and is defined and evaluated as follows:

$$\vec{V}_R = \vec{V}_{SH} - \vec{V}_T = (V_{SH}\,\mu_X - V_T)\,\vec{i} + V_{SH}\,\mu_Y\,\vec{j} + V_{SH}\,\mu_Z\,\vec{k} \tag{8}$$

$$V_R = \sqrt{V_{SH}^2 - 2\,V_{SH}\,V_T\,\mu_X + V_T^2} \tag{9}$$

Let A, B, and C be the direction cosines of $\vec{V}_R$ with respect to the X, Y, and Z axes.

$$A = \frac{V_{SH}\,\mu_X - V_T}{V_R} \tag{10}$$

$$B = \frac{V_{SH}\,\mu_Y}{V_R} \tag{11}$$

$$C = \frac{V_{SH}\,\mu_Z}{V_R} \tag{12}$$

The D_M is the closest approach distance of the trajectory to the aim point which in this case, is the center of gravity of the target. The method used to choose a value for D_M depends on the weapon type.

For the weapons with fragmenting warheads, an σ_A (aiming sigma) is an input. The value of D_M is chosen randomly from a normal distribution having mean zero and standard deviation σ_A.

The solid shot weapons are characterized by a table of mil errors as a function of target velocity. The E_M (probable aiming error expressed in mils) can be found for any V_T by interpolation in this table. Let the altitude of the target be H, and the R_S (slant range) is given by:

$$R_S = H/\sin(El) \tag{13}$$

The E_P (probable aiming error expressed in units of linear measure) can be calculated from:

$$E_P = 0.001\, R_S\, E_M \tag{14}$$

For normal distribution, the E_P is equal to 0.675 standard deviation units. Thus, for the aiming error.

$$\sigma_A = E_P/0.675 \tag{15}$$

Given the aiming error, the D_M defines the radius of a circle in the plane perpendicular to the V_R and centered at the aiming point. The following procedure chooses a point (X_O, Y_O, Z_O) at random on the circumference of the circle. This point and the V_R defines the trajectory for a single shot.

Select an r_u uniformly distributed between zero and one. Let $\phi = 2\pi\, r_u$. A, B, and C are the direction cosines of $\vec{V}_R$ as calculated from equations (10), (11), and (12). If $C \neq 1$, let:

$$\cos\psi = -\frac{A}{\sqrt{A^2 + B^2}}$$

$$\sin\psi = \frac{B}{\sqrt{A^2 + B^2}}$$

Then,

$$X_O = |D_M|\,[C\cos\phi\cos\psi + \sin\phi\sin\psi] \tag{16}$$

$$Y_O = |D_M|\,[-C\cos\phi\sin\psi + \sin\phi\cos\psi] \tag{17}$$

If C = 0,

$$Z_O = |D_M|\cos\phi \tag{18}$$

Otherwise,

$$Z_O = (-AX_O - BY_O)/C \tag{19}$$

If C = 1, the following equations apply:

$$X_o = |D_M| \cos \phi \tag{20}$$

$$Y_o = |D_M| \sin \phi \tag{21}$$

$$Z_o = 0 \tag{22}$$

GEOMETRY OF SOLID SHOT ENCOUNTER

For solid shot weapons, a hit is said to occur if the trajectory intersects any fuel tank. Consider the case of one tank having dimensions LT, WT, and HT, and centroid located at (X_{CG}, Y_{CG}, and Z_{CG}). For a given trajectory there are, at most, three faces of the tank through which it is possible for the shell to enter. These can be determined from the direction cosines of the $\vec{V}_R$ as shown:

<0	=0	>0
Front	No intercept with front or rear	Rear
Left	No intercept with side	Right
Top	No intercept with top or bottom	Bottom

The procedure for determining whether a hit occurs is to find the coordinates of the points which represent the intersection of the trajectory with those planes (taken from Table 2) in which the faces of the tank lie. These points are examined to determine whether they fall within the bounds which form the faces of the tank. For example, the planes which contain the top and bottom faces of the tank are parallel to the XY plane, and their equations are, respectively:

$$Z = Z_{CG} + HT/2 \tag{23}$$

$$Z = Z_{CG} - HT/2 \tag{24}$$

The equation of the trajectory is:

$$\frac{X - X_o}{A} = \frac{Y - Y_o}{B} = \frac{Z - Z_o}{C} \tag{25}$$

Let (X_{IN}, Y_{IN}, Z_{IN}) be the intersection point of the trajectory with whichever plane, (23) or (24), is encountered by the shell first. Then, using Table 1 and equations (23) and (24):

$$Z_{IN} = Z_{CG} + HT/2, \ C<0$$

$$Z_{IN} = Z_{CG} - HT/2, \ C>0$$

Substituting this value of Z_{IN} into equation (25):

$$X_{IN} = A/C\ (Z_{IN} - Z_o) + X_o$$

$$Y_{IN} = B/C\ (Z_{IN} - Z_o) + Y_o$$

If C is equal to zero, the trajectory is parallel to the top and bottom faces and the point (X_{IN}, Y_{IN}, Z_{IN}) does not exist. This point indicates a hit on the top or bottom face of the tank if the following conditions are satisfied:

$$X_{CG} - LT/2 \leq X_{IN} \leq X_{CG} + LT/2$$

$$Y_{CG} - WT/2 \leq Y_{IN} \leq Y_{CG} + WT/2$$

If a hit is not found on the top or bottom face, the sides and the front/rear faces are checked by a procedure similar to the above. If a valid entry point is found for one of the three possible faces, the other three faces are checked to determine the exit point. Based on the percent of fuel remaining, it is determined whether the entry and exit points are above or below the fuel.

GEOMETRY OF FRAGMENTING WARHEAD ENCOUNTER

The method of treating the fragmenting warhead is to determine the burst point and solve, using an iterative procedure, the equation which relates distance and time traveled for the fragments. Having solved this equation, and knowing the fragment density, it is possible to calculate the expected number of hits on a tank and the probability of a kill.

The standard deviation of the fuzing error along the trajectory is σ_F. The aiming point for this type of weapon is not assumed to be the center of gravity, but is input as (X_{FUSE}, Y_{FUSE}, and Z_{FUSE}). The error along the trajectory due to fuzing is taken from the point of closest approach to (X_{FUSE}, Y_{FUSE}, and Z_{FUSE}). This error, D_F, is chosen at random from a normal distribution having mean of zero and standard deviation σ_F. For a burst point located by X*, Y*, Z*:

$$X^* = X_o + Y_{FUSE} + D_F\ (\mu_X - V_T/V_{SH})$$

$$Y^* = Y_o + Y_{FUSE} + D_F\ \mu_Y$$

$$Z^* = Z_o + Z_{FUSE} + D_F\ \mu_Z$$

The explosion of a static fragment warhead yields a characteristic spectrum of fragment mass, angular density, and emission velocity. The explosion of a moving fragment warhead alters this spectrum by virtue of the velocity of the velocity of the projectile. It is necessary to determine the interaction of this altered spectrum with the target. The relationship between speed and direction of the projectile, and the speed and direction of an emitted fragment are derived using Figure 4. The V_E (fragment emission velocity) and the angle θ are those observed in a static explosion; while, through vector addition, V_O (observed fragment velocity) and angle γ occur in a dynamic explosion.

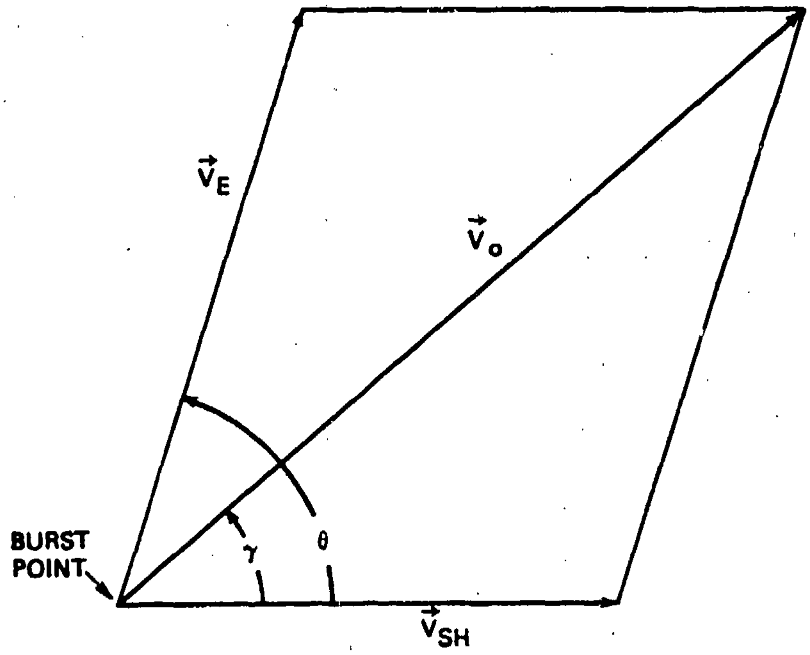

Figure 4. Static and Dynamic Fragment Emission.

The law of cosines applied to Figure 4 yields a quadratic equation for V_o:

$$V_o = V_{SH} \cos \gamma \pm \sqrt{(V_{SH} \cos \gamma)^2 + V_E^2 - V_{SH}^2}$$

If $V_{SH} < V_E$, as is usually true, the negative root leads to a negative velocity which is ruled out. Thus, equation (26) is valid and emission velocity is single-valued for a given γ when $V_{SH} \leq V_E$:

$$V_o = V_{SH} \cos \gamma + \sqrt{(V_{SH} \cos \gamma)^2 + V_E^2 - V_{SH}^2} \tag{26}$$

Another relationship results from Figure 4 by summing vector components in the $\vec{V}_{SH}$ direction:

$$\cos \theta = \frac{V_o \cos \gamma - V_{SH}}{V_E} \tag{27}$$

The fragment ballistics must be considered. A stationary x, y, z coordinate system is employed. This coordinate system is defined to coincide with the X, Y, Z system at the t=O (time of the explosion). The explosion point in the x, y, z system is at (x^*, y^*, z^*), where:

$$x^* = X^*$$

$$y^* = Y^*$$

$$z^* = Z^*$$

The target is represented by a set of fuel tanks, and the location of each tank is designated by the coordinates of its center of gravity. It must be determined whether each tank is hit by the fragment spray, and if so, what the expected number of hits will be.

Using this procedure for one tank, consider a tank located at point (X_{CG}, Y_{CG}, Z_{CG}). At t=0, the tank coordinates in the stationary system are (x, y, z) = (X_{CG}, Y_{CG}, Z_{CG}). The tank is moving in the +x direction; therefore, the hit point occurs one time-of-flight later at point (x, y, z) = x_H, Y_{CG}, Z_{CG}). At this point the fragment has traveled a distance L, where:

$$x_H = X_{CG} + V_T t \tag{28}$$

$$L = \sqrt{(x_H - x^*)^2 + (Y_{CG} - y^*)^2 + (Z_{CG} - z^*)^2} \tag{29}$$

The direction cosines, with respect to the x, y, z axes, of the line from explosion point to hit point are β_x, β_y, and β_z:

$$\beta_x = \frac{x_H - x^*}{L} \tag{30}$$

$$\beta_y = \frac{Y_o - y^*}{L} \tag{31}$$

$$\beta_z = \frac{Z_o - z^*}{L} \tag{32}$$

With the direction cosines of each vector known, the angle γ (Figure 4) is given by taking the scalar product of the vectors:

$$\cos \gamma = \mu_x \beta_x + \mu_y \beta_y + \mu_z \beta_z \tag{33}$$

The distance-time relationship, which describes the fragment travel, can be derived. By equating the inertial and drag forces for geometrically similar bodies, it can readily be shown that the logarithmic derivative of velocity with travel is proportional to the air density, and inversely proportional to any characteristic length of the body. The proportionality constant is determined by the drag coefficient, the mass density of the body, and the geometrical shape. Thus, for fragments having some characteristic mass spectrum, a sea level slowdown constant (k) may be introduced whose value will be independent of mass:

$$\frac{d \ln V}{d L} = - k \frac{\rho}{m^{1/3}}$$

where V is the velocity of a fragment after traveling a distance L, ρ is the relative air density, and m is the fragment mass. This may be integrated at constant drag coefficient to yield the velocity-distance equation for fragments, where V_o is the initial fragment speed:

$$\ln (V/V_o) = - k \rho L/m^{1/3}$$

This equation is integrated once more to obtain the desired result:

$$B\,V_o t = e^{BL} - 1 \tag{34}$$

where

$$B = k\,\rho/m^{1/3}$$

The criterion for a hit and all corresponding properties are determined by simultaneous solution of equations (26), (28), (29), (30), (31), (32), and (34). No analytic solution to this system has been found, but an iterative numerical solution can be employed.

The numerical method is the Newton-Raphson technique. The formulation of this method, as applied to fragments, has been tested and found to give rapid convergence even with inputs which were known to be troublesome by previous methods. The Newton-Raphson method obtains the roots of $F(t) = 0$.

The classical method takes the J^{th} estimate of the root t^J and extracts the $(J+1)$ estimate $t^{(J+1)}$ by means of equation (35):

$$t^{(J+1)} = t^{(J)} - \frac{F(t^J)}{\dot{F}(t^J)} \tag{35}$$

The procedure is repeated until successive estimates are considered to differ negligibly. Application of this method to the fragment ballistics required suitable choice of $F(t)$. The travel-time relation (34) is chosen and rewritten as the F function:

$$F(t) = \ln\,(1 + B\,V_o\,t) - B\,L \tag{36}$$

Differentiation yields the time derivative:

$$\dot{F}(t) = B\left[\frac{V_o + \dot{V}_o\,t}{1 + B\,V_o\,t} - \dot{L}\right] \tag{37}$$

The two time derivatives in equation (37) must be evaluated from the other relations that must be satisfied.

Differentiation of equation (26) at constant V_E yields:

$$\dot{V}_o = \left[\frac{-V_o\,V_{SH}\sin\gamma}{V_o - V_{SH}\cos\gamma}\right]\dot{\gamma} \tag{38}$$

Differentiation of equation (28) yields:

$$\dot{x}_H = V_T \tag{39}$$

Differentiation of equation (29), and use of (30) and (39) yields:

$$\dot{L} = \beta_x\,V_T \tag{40}$$

It can be seen that while L is known in terms of non-derivatives $\dot{V}_o$ is known in terms of $\dot{\gamma}$. Thus, to complete the evaluation of equation (37), it is necessary to calculate $\dot{\gamma}$.

Differentiation of equations (30), (31), and (32), and using (39) yields:

$$\dot{\beta}_x = \frac{V_T - \beta_x \dot{L}}{L} \tag{41}$$

$$\dot{\beta}_y = \frac{-\beta_y \dot{L}}{L} \tag{42}$$

$$\dot{\beta}_z = \frac{-\beta_z \dot{L}}{L} \tag{43}$$

Differentiation of equation (33) and employing (41), (42), and (43) gives:

$$\dot{\gamma} = \frac{\dot{L} \cos \gamma - \mu_x V_T}{L \sin \gamma} \tag{44}$$

The final results are obtained by eliminating $\dot{L}$ and $\dot{\gamma}$ between equations (37), (38), (40), and (44):

$$\dot{F}(t) = B \left[\frac{V_o + \dot{V}_o t}{1 + B V_o t}\right] - \beta_x V_T \tag{45}$$

$$\dot{V}_o = \left[\frac{V_o V_{SH} V_T}{L}\right] \left[\frac{\mu_x - \beta_x \cos \gamma}{V_o - V_{SH} \cos \gamma}\right] \tag{46}$$

Thus, the Newton-Raphson method for fragment ballistics employs the system of equations (35), (36), (45), and (46).

The method used to determine the hit point of a given fuel tank for a fragment of a given mass is:

a. Estimate time-of-flight (t).

b. Calculate hit point coordinate (x_H) from equation (28).

c. Calculate fragment travel (L) from equation (29).

d. Calculate direction cosines (β_x, β_y, and β_z) of fragment velocity from equations (30), (31), and (32).

e. Calculate dynamic fragment emission angle (γ) from equation (33).

f. Calculate dynamic fragment emission velocity (V_o) from equation (26).

g. Calculate F(t) from (26) and $\dot{V}_0$ from equation (46).

h. Calculate $\dot{F}(t)$ from equation (45). If $\dot{F}(t) < 0$, there is no hit point and the fragment has missed the fuel tank.

i. Make new estimate of time-of-flight (t) using equation (35). If the new t<0, score a miss; otherwise, compare with the previous value of t. If two successive values are in agreement (e.g., result in a difference of less than 0.5 foot in the hit point), the process is considered to have converged and the most recent value of t is saved as the solution. Otherwise, iterate again at step c.

It is important to make a good estimate of the time-of-flight for step a. The method used for the first estimate is to take the analytic solution for the case of zero fragment slowdown.

The distance-time relationship for the zero slowdown case is:

$$L = V_o t \tag{47}$$

With a substantial amount of algebraic manipulation, equation (48) is combined with (26), (28), (29), (30), (31), (32), and (33) to yield:

$$K_1 t^2 + K_2 t + K_3 = 0 \tag{48}$$

where

$$K_1 - V_R^2 - V_E^2$$

$$K_2 = -2\, V_{SH} \left[\left(\mu_x - \frac{V_T}{V_{SH}}\right) (X_{CG} - x^*) + \mu_y \; (Y_{CG} - y^*) + \mu_z \, (Z_{CG} - z^*) \right]$$

$$K_3 = (X_{CG} - x^*)^2 + (Y_{CG} - y^*)^2 + (Z_{CG} - z^*)^2$$

The solution to this equation is:

$$t = -\frac{K_2}{2K_1} \pm \sqrt{\left(\frac{K_2}{2K_1}\right)^2 - \left(\frac{K_3}{K_1}\right)}$$

The smaller positive value of t from the above solution is used as the initial estimate for the iterative procedure.

When the iterations have been found to converge for a particular fuel tank, the value of cos θ is determined from equation (27). This value is compared with the limits of the static fragment spray. If the value lies outside these limits, the shot is scored as a miss. If cos θ lies within the bounds of the static fragment spray limits, it is necessary to calculate the fragment density resulting from the dynamic explosion.

The model assumes that the fragment density resulting from a static explosion is uniform between the fragment spray limits. Let ξ be this density expressed in fragments per steradian. As a result of the rotation of velocity vectors due to the projectile motion, the fragment density in the static case at angle θ is not equal to the dynamic density at angle γ. This effect may be calculated using the geometry of Figure 4.

The solid angle subtended by the conical shell between θ and $\theta + d\theta$ is $d\omega_\theta$:

$$d\omega_\theta = \frac{[V_E\, d\theta]\ [2\pi\, V_E \sin\theta]}{V_E^2} = 2\pi \sin\theta\, d\theta$$

Similarly, the solid angle of the conical shell between γ and γ+d is $d\omega_\gamma$:

$$d\omega_\gamma = \frac{[V_O\, d\gamma]\ [2\pi\, V_O \sin\gamma]}{V_O^2} = 2\pi \sin\gamma\, d\gamma$$

Assuming that adjacent rays satisfy the geometry of Figure 1, the number of fragments in each of these conical shells is the same; thus, E is a measure of the change in fragment density, where:

$$E = \frac{d\omega_\gamma}{d\omega_\theta} = \frac{\sin\gamma}{\sin\theta}\ \frac{d\gamma}{d\theta} \tag{49}$$

$$\xi_{DYN} = \xi/E \tag{50}$$

To calculate the value of ξ_{DYN}, E must be derived for use in equation (50).

The speed ratio G is defined as:

$$G = \frac{V_E}{V_{SH}}$$

Elimination of V_o between equations (26) and (27) gives:

$$\cos^2\gamma + G^2 - 1 = \frac{G\cos\theta + 1}{\cos\gamma} \cdot \cos\gamma$$

Squaring and rearranging terms yields:

$$\cos^2\gamma = \frac{(1 + G\cos\theta)^2}{(G^2 + 2\,G\cos\theta + 1)}$$

Differentiating equation (51) results in:

$$\frac{d\gamma}{d\theta} = \frac{G^2 \sin\theta\,(1 + G\cos\theta)\,(G + \cos\theta)}{\cos\gamma\,\sin\gamma\,(G^2 + 2\,G\cos\theta + 1)^2}$$

Substituting this result in equation (40):

$$E = \frac{G^2\,(1 + G\cos\theta)\,(G + \cos\theta)}{\cos\gamma\,(G^2 + 2\,G\cos\theta + 1)^2} \tag{52}$$

Further simplification results by eliminating $\cos\gamma$ between equations (51) and (52). Based on the geometry of the situation, it is concluded that E is non-negative.

$$E = \frac{G^2|C + \cos\theta|}{(G^2 + 2\,G\cos\theta + 1)^{3/2}} \tag{53}$$

PROBABILITY OF FRAGMENT DAMAGE TO FUEL TANKS

The fuel tank is treated as a rectangular parallelepiped; therefore, there are a maximum of three faces that can be hit due to one explosion. Identification of the three faces can be achieved by the use of relative velocities.

V_{HIT} (fragment speed at the time of the hit) is found to be:

$$V_{HIT} = V_o e^{-BL}$$

The striking fragment, target, and relative $\vec{V}_{NET}$ velocities can now be expressed:

$$\vec{V}_{HIT} = V_{HIT}\,\beta_x\,\vec{i} + V_{HIT}\,\beta_y\,\vec{j} + V_{HIT}\,\beta_z\,\vec{k}$$

$$\vec{V}_T = V_T\vec{i}$$

$$\vec{V}_{NET} = \vec{V}_{HIT} - \vec{V}_T = (V_{HIT}\,\beta_x - V_T)\,\vec{i} + V_{HIT}\,\beta_y\,\vec{j} + V_{HIT}\,\beta_z\,\vec{k}$$

The V_{NET} (net striking speed) is the magnitude of the velocity $\vec{V}_{NET}$:

$$V_{NET} = \sqrt{V_{HIT}^2 - 2\,V_T\,V_{HIT}\,\beta_x + V_T^2}$$

The signs of the $\vec{V}_{NET}$ components identify the struck aspects as follows:

	<0	=0	>0
β_z	Top	No strikes on top or bottom	Bottom
β_y	Left	No strikes on sides	Right
$\beta_x - \dfrac{V_T}{V_{HIT}}$	Front	No strikes on front or rear	Rear

The number of fragment hits on each of the three aspects remains to be calculated. Calculation of the fragment density in target coordinates appears tedious and possibly difficult. Therefore, the approximation is made that the number of hits can be calculated on a static target. This should be an excellent approximation if $V_{HIT} >> V_T$ and probably not too bad for most cases to be encountered. Using the static target concept, Table 2 is modified, replacing V_T/V_{HIT} by zero.

Consider a static target placed in a constant density pulsed beam of particles emitted from a static point source. To be definite, consider the right-left aspect only. The actual area of the aspect is A_y, while the area component normal to the beam is $A_y|\beta_y|$. The solid angle viewed by the point source is approximately $A_y|\beta_y|/L^2$. If the separation L is quite small, this will give a large overestimate of the solid angle, but this is not important since kill will be achieved for small L. Thus, the number of hits on the aspect is $\xi_{DYN} A_y|\beta_y|/L^2$. From this and equation (50), the following result is generalized for the i^{th} aspect:

$$n_i = \frac{\xi A_i|\beta_i|}{EL^2} \tag{54}$$

where n_i is the number of hits on the i^{th} aspect.

If N is the total number of fragments emitted by the warhead, the probability that a fragment selected at random scores a hit on the i^{th} aspect is:

$$p_i = \frac{n_i}{N}$$

Considering each fragment to be independent of other fragments in hitting a fuel tank, the P_H based on the appropriate three faces can be formulated by:

$$1-P_H = \prod_{\substack{\text{three}\\\text{faces}}}(1-p_i)^N = \prod(1-p_i)^{\left(-\frac{1}{p_i}\right)(-n_i)}$$

$$\simeq \prod_{\substack{\text{three}\\\text{faces}}} e^{-n_i} = e^{-\Sigma n_i}$$

where the approximation is good only for $p_i << 1$. Substituting from equation (54), the final form is:

$$P_H = 1 - e^{-\sum_{\substack{\text{three}\\\text{faces}}} \frac{\xi A_i|\beta_i|}{EL^2}} \tag{55}$$

Similarly, the P_{BF} (probability of a hit below the fuel level) and the P_{AF} (probability of a hit above the fuel level) can be calculated from:

$$P_{BF} = 1 - e^{-\Sigma \frac{\xi A_i'|\beta_i|}{EL^2}} \tag{56}$$

$$P_{AF} = 1 - e^{-\Sigma \frac{\xi A_i''|\beta_i|}{EL^2}} \tag{57}$$

where A_i' represents that portion of the i^{th} aspect area which is below the fuel level, and A_i'' represents that portion of the i^{th} aspect area which is above the fuel level.

The probability of a leak is considered to be equal to the P_{BF}. The P_{EF} (probability that an external fire occurs given that a leak exists) is calculated from:

$$P_{EF} = P_{BF}D_{EF} \tag{58}$$

D_{EF} is a degradation factor which is dependent upon the altitude at which the encounter takes place and the temperature of the fuel in the tank:

$$D_{EF} = \begin{cases} 0.3 & H>60{,}000, \text{ or } H<10{,}000 \text{ and } T<0, \text{ or } T>45 \\ 0.3(T/45) & H>60{,}000, \text{ or } H<10{,}000 \text{ and } 0\leq T\leq 45 \\ 0.3(1.2-.00002H) & 10{,}000\leq H\leq 60{,}000 \text{ and } T<0, \text{ or } T>45 \\ 0.3(T/45)\,(1.2-.00002H) & 10{,}000\leq H\leq 60{,}000 \text{ and } 0\leq T\leq 45 \end{cases}$$

where T is the fuel temperature in degrees Fahrenheit, and H is the altitude in feet. This relationship for the degradation factor is based on limited data for wet hit test results[2]

The P_{FE} (probability of an internal fire/explosion) is considered to be zero unless the fuel-to-air ratio in the ullage space is within the flammability limits for the particular fuel being used. If the fuel-to-air ratio lies within the flammability limits (e.g., 0.013 to 0.08 for JP-4), this probability is given by:

$$P_{FE} = P_{AF}D_{FE} \tag{59}$$

where

$$D_{FE} = \begin{cases} .00000769m^{1/2}\, V_{NET} & H<10{,}000 \\ .00000769m^{1/2}\, V_{NET}\left(2.5e^{-.00092H}\right) & H\geq 10{,}000 \end{cases}$$

This relationship was derived by fitting curves to data supplied by BRL.

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[2]Ballistic Research Laboratory. *Fragment Firings Against Aircraft Fuels at Simulated Altitude*, by W.R. Harris. Aberdeen Proving Ground, MD, BRL, October 1953. (BRL TN 828, publication UNCLASSIFIED.)

The last type of damage mechanism which is considered by the model is damage due to hydraulic ram. This mechanism is treated from an energy density standpoint. If the energy density of the fragment spray on a particular fuel tank is above a threshold value, ram is said to occur on this tank for this explosion. The energy density of the spray is calculated from the relationship:

$$E_{RAM} = \left[\frac{mV_{NET}^2}{2}\right] \left[\frac{\xi}{EL^2}\right]$$

APPLICATIONS

The model can be used to examine variations in the type and intensity of threat as the mission profile changes. The vulnerability characteristics of the aircraft vary with time, maneuver history, threat, and threat exposure. For example, aircraft which penetrate and/or deliver ordnance at low altitude may be exposed to a greater variety of hostile weapons than high altitude bombers. Any given weapon system may be exposed to a wide variation in lethal threat as its flight profile is changed. Exercise of the model will reveal the relative severity of the threats and indicate potential phases for laboratory testing.

In the case of a large bomber, for example, it is not immediately obvious whether concern should be directed at air-to-air missiles in the cruise-out phase, or at light AAA weapons in the low altitude approach. At high altitude, ullage spaces tend to be oxygen-poor and quite cool, which inhibits propagating fires. At low altitude, the fuel-air mix, particularly immediately following descent, may reach near-optimum flammability, and even an otherwise minor threat may become lethal. Aerodynamic heating late in a low altitude phase may produce flammable mixtures.

CONCLUSIONS

The vulnerability model presents a system for studying the dynamic interaction between fuel state and hostile threat. Previous systems have studied the fuel system statistically, with dynamic treatment of weapons only.

There are several limitations in this model. Ullage spaces were assumed to be homogeneous. The effects of vent geometry, slosh, vibration, and splash caused by impact were not treated. There was no integration of the fuel system into the aircraft structure (masking and shielding by other components). Secondary ignition sources were only crudely treated. Tank geometry was limited to rectangular shapes. Round breakup and ricochet were not treated.

This project was exploratory in nature. The results achieved represent an improvement in treating fuel system vulnerability. Vulnerability can now be calculated as a function of the mission style, as opposed to the single point computations previously possible. This represents a large increase in the realism of vulnerability computations.

Appendix

PROGRAM LISTING AND SAMPLE CASE

WSFT PROGRAM

```
JOBWSFT,CM50000,T160,I0100,P6.
FTN(OPT=0)
LGO(,,,,TNK1)
 ATALOG(TNK1,TNK1,RP=10,RN=1)
9  END OF RECORD
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6=OUTPUT,TAPE7)
      COMMON/TITL/CID(12)
      COMMON/STIR/ RGAS,EMWA,EMWF,CPA,CPF,HJ(3),ULLGH,ULWID,ULHT,
     1DELHF,ZOG,AV,CP,EMW,DV,CDELTA,KTANK,GALO,TVENT
      COMMON/EULIN/ DUMMY(9),EM,TA,Z,EMV,EMOG,EMEV,EMCD,V,GAL
      COMMON/OUTGAS/BETA,CON1,CON2,RHOLIQ,EMDISO,SUMMDO,EMDDOT
     1,VLIQ,EMDIS,EMDISE
      COMMON/LIMITS/TO,TMAX,DT,TPRNT,DTPRNT,TIME,M16
      COMMON/TABLS/TAB(100,2,8), NTAB(8),NSAVE(8)
      COMMON /FILE7/ FAR(250),FLEFT(250),FTEMP(250),HT(250),VT(250),
     1ITPRNT,GALX,TINC
      DIMENSION HDR(8)
      DIMENSION   TF(100,2),TSIDE(100,2),TTOP(100,2),DUM(1)
     $          ,ALT(100,2), GALDOT(100,2), PVAP(100,2), EMINF(100,2)
      EQUIVALENCE    (TAB(1,1,2) , TF(1,1)         )
     $              ,(TAB(1,1,3) , TSIDE(1,1)      )
     $              ,(TAB(1,1,4) , TTOP(1,1)       )
     $              ,(TAB(1,1,5) , ALT(1,1)        )
     $              ,(TAB(1,1,6) , GALDOT(1,1)     )
     $              ,(TAB(1,1,7) , PVAP(1,1)       )
     $              ,(TAB(1,1,8) , EMINF(1,1)      )
     $              ,(DUM(1), TAB(1,1,1) )
      NAMELIST/DATA/RGAS,EMWA,EMWF,CPA,CPF,TA,HJ,ULLGH,ULWID,
     $    ULHT,DELHF,ZOG,AV,DV,CDELTA,KTANK,GALO,BETA,CON1,CON2
     $   ,TVENT
     $   ,TF,TSIDE,TTOP,ALT,GALDOT,PVAP,EMINF
     $    ,TO,TMAX,DT,DTPRNT
      DATA HDR/1H ,2HTF,5HTSIDE,4HTTOP, 3HALT, 6HGALDOT, 4HPVAP,
     1    5HEMINF /
      DO 5 I=1,1600
      DUM(I)= -992.1
 5    CONTINUE
      ITPRNT=0
      IPRT=0
 50   READ(5,900)CID
 900  FORMAT(12A6)
      IF(EOF(5))1000,10
   10 READ(5,DATA)
      TINC=DTPRNT
      GALO=GALO
      TIME=TO
      TPRNT= TO  +DTPRNT
      DT= AMIN1(DT,DTPRNT)
      TOL =  AMAX1( .0001*DT,1.0E-8)
      WRITE(6,910)
 910  FORMAT(1H1,20X,12HINPUT TABLES )
      DO 75 I=2,8
      WRITE(6,920) HDR(I)
 920  FORMAT(1H0,25X,10HTABLE (OR , A6/)
      NSAVE(I)=1
      DO 74 J=1,100
      IF( TAB(J,1,I) .EQ.-992.1 .AND. TAB(J,2,I).EQ.-992.1)GO TO 75
      WRITE(6,930) J,TAB(J,1,I),TAB(J,2,I)
 930  FORMAT(15X,I5,2E17.7)
      NTAB(I)=J
```

```
      SUBROUTINE LINI(X,Y,N,ARG,YARG,NSAVE)
C
C         LINEAR INTERPOLATION ROUTINE
C
      DIMENSION X(1),     Y(1)
      NN=N
      XV=ARG
      IF (XV.GE.X(NN))GO TO 40
      IF(XV.LE.X(1))GO TO 50
C
      J= NSAVE
      IF(J .LT. 1 .OR. J .GT. NN) J=1
      K= SIGN(1.0,(XV-X(J)))
    5    J=J+K
      IF( (XV-X(J) )* FLOAT(K) ) 10,30,5
   10 IF(K.EQ.-1)J=J+1
      I=J-1
C
C              INTERPOLATION CALC
C
      H=X(J)-X(I)
      DX=XV-X(I)
      DY=Y(J)-Y(I)
      YARG= Y(I) +  DX*DY/H
      NSAVE=I
      RETURN
   30 YARG=Y(J)
      NSAVE=J
      RETURN
   40 YARG=Y(NN)
      RETURN
   50 YARG=Y(1)
      RETURN
      END
```

```
 35     IF(ABC(DET) .EQ. 0.) GO TO 50
C       COMPUTE DETERMINANT
        DO 40 I=1,N
 40     DET = DET*A(I,I)*S(I)
C       BACK SUBSTITUTE
 50     A1 = A(N,N)
        DO 70 J=1,M
        JJ = N+J
        X(N,J) = A(N,JJ)/A1
        IF(N .EQ. 1) GO TO 70
        DO 65 I=2,N
        K = MN-I
        A2 = A(K,K)
        IF(ABC(A2) .LE. 1.D-10) GO TO 110
        B = A(K,JJ)
        LL = K+1
        DO 60 L=LL,N
 60     B = B-A(K,L)*X(L,J)
 65     X(K,J) = B/A2
 70     CONTINUE
        LA = 0
        RETURN
 100    LA = 1
        RETURN
 110    LA = -1
        RETURN
        END
```

```
        REAL FUNCTION LIN(ARG,N)
        COMMON/TABLS/TAB(100,2,8), NTAB(8),NSAVE(8)
        CALL LIN1(TAB(1,1,N),TAB(1,2,N),NTAB(N),ARG,Y,NSAVE(N) )
        LIN= Y
        RETURN
        END
```

```
      SUBROUTINE LESK(A,X,S,N1,M1,N1X,DET,LA)
      DIMENSION A(N1X,1),X(N1X,1),S(N1X)
C     THIS ROUTINE IS A SINGLE PRECISION LINEAR EQUATION
C     SOLVER. IN ORDER TO CONVERT TO COMPLEX OR DOUBLE-
C     PRECISION, REMOVE THE FOLLOWING CARD.
      ABC(DET) = ABS(DET)
C     THEN, IF DOUBLE-PRECISION IS DESIRED, REMOVE
C     THE COL 1 C IN EACH OF THE NEXT TWO CARDS.
C     DOUBLE PRECISION A,X,S,DET,AS,A1,A2,R,B
C     ABC(DET) = DABS(DET)
C     IF INSTEAD COMPLEX IS DESIRED, REMOVE THE COL 1 C
C     IN EACH OF THE NEXT TWO CARDS.
C     COMPLEX A,X,DET,A1,A2,R,B
C     ABC(DET) = CABS(DET)
      N = N1
      M = M1
      MN = N+1
      NM = N+M
C     GET SCALE FACTORS
      DO 10 I=1,N
      S(I) = ABC(A(I,1))
      DO 5 J=1,N
      DA = ABC(A(I,J))
      IF(DA .LE. S(I)) GO TO 5
      S(I) = DA
  5   CONTINUE
      IF(S(I) .EQ. 0.) GO TO 100
 10   CONTINUE
C     SCALE ROWS
      DO 15 I=1,N
      AS = 1./S(I)
      DO 15 J=1,NM
 15   A(I,J) = AS*A(I,J)
C     START TRIANGULARIZATION PROCESS
      IF(N .EQ. 1) GO TO 35
       NO = N- 1
      DO 30 I=1,NO
      K = I
      DA = ABC(A(I,I))
      DO 18 J=I,N
      DB = ABC(A(J,I))
      IF(DB .LE. DA) GO TO 18
      K = J
      DA = DB
 18   CONTINUE
      IF(DA .EQ. 0.) GO TO 30
      IF(K .EQ. I) GO TO 22
      DO 20 J=I,NM
      B = A(K,J)
      A(K,J) = A(I,J)
 20   A(I,J) = B
      DET = -DET
 22   II = I+1
      DO 29 J=II,N
      R = A(J,I)/A(I,I)
      DO 28 K=II,NM
 28   A(J,K) = A(J,K)-R*A(I,K)
 29   CONTINUE
 30   CONTINUE
      IF(ABC(A(N,N)) .LE. 1.D-10) GO TO 110
```

```
      SUBROUTINE INITIL
      COMMON/LIMITS/TO,TMAX,DT,TPRNT,DTPRNT,TIME,M16
      COMMON/STIR/ RGAS,EMWA,EMWF,CPA,CPF,HJ(3),ULLGH,ULWID,ULHT,
     1DELHF,ZOG,AV,CP,EMW,DV,CDELTA,KTANK,GALO,TVENT
      COMMON/EULIN/ DUMMY(9),EM,TA,Z,EMV,EMOG,EMEV,EMCD,V,GAL
      COMMON/OUTGAS/BETA,CON1,CON2,RHOLIQ,EMDISO,SUMMDO,EMDDOT
     1,VLIQ,EMDIS,EMDISE
      REAL LIN
      NAMELIST/CKINPT/ RGAS,EMWA,EMWF,CPA,CPF,TA,HJ,
     1  ULLGH,ULWID,ULHT,DELHF,ZOG,AV,DV,CDELTA,KTANK,GALO
C
C
      SUMMDO = 0.0
      EMV = 0.
      EMEV = 0.
      EMOG = 0.
      EMCD = 0.
      GAL  = 0.
      TA = TA +459.7
      IF(KTANK .EQ. 1) GO TO 100
      V = ULLGH*ULWID*ULHT
      GO TO 200
  100 V = 3.14159265* ULWID**2*ULLGH/4. -GALO*231./1728.
 200  ALT=LIN(TIME,5)
      ALT = ALT*1000.0
      CALL ATMOS(ALT,TALT,PR,DUMM,DUM1,DUM2)
      TF= LIN(TIME,2)
      PVAP = LIN( TF,7)
      TF = TF +459.7
      PPFUEL = PVAP*144.
      PPAIR =  PR - PPFUEL
      RHO  =  (PPFUEL*EMWF + PPAIR*EMWA)/(RGAS*TA)
      EM =  RHO*V
      Z  =  PPAIR*EMWA/(RHO*RGAS*TA)
      VLIQO = GALO*231./1728.
      EMWOG = EMWA
      EMDISO = (BETA*EMWOG*VLIQO*PPAIR)/(.797*453.*2116.224)
C
      WRITE(6,CKINPT)
C
      RETURN
      END
```

```
      SUBROUTINE EULER
      COMMON/LIMITS/TO,TMAX,DT,TPRNT,DTPRNT,TIME,M16
      DIMENSION X(9),XDOT(9)
      COMMON/EULIN/ XDOT,X
      COMMON/OUTGAS/BETA,CON1,CON2,RHOLIQ,EMUIS0,SUMMDO,EMDDOT
     1,VLIQ,EMUIS,EMUISE
C
C
      DO 10 I = 1,9
      X(I)= X(I) + XDOT(I)*DT
 10   CONTINUE
      SUMMDO = SUMMDO   + EMDDOT* DT
C
      RETURN
      END
```

```
      SUBROUTINE FUNCT
      COMMON/STIR/ RGAS,EMWA,EMWF,CPA,CPF,HJ(3),ULLGH,ULWID,ULHT,
     1DELHF,ZOG,AV,CP,EMW,DV,CDELTA,KTANK,GALO,TVENT


      COMMON/EULIN/ MDOT,TDOT,ZDOT, MDOTV, MDOTOG, MDOTEV, MDOTCD,VDOT,
     1GALDOT,
     2EM,TA,Z,EMV,EMOG,EMEV,EMCD,V,GAL
      COMMON/ETC/ ALT,AJ(3),TJ(3),RHOV,PR,PPAIR,PPFUEL,PPFLQS,
     1 AMACH,DALTDT,PDOT,OF,MASRAT,UVENT
      COMMON/OUTGAS/BETA,CON1,CON2,RHOLIQ,EMUIS0,SUMMDO,EMDDOT
     1,VLIQ,EMUIS,EMUISE
      COMMON/LIMITS/TO,TMAX,DT,TPRNT,DTPRNT,TIME,M16
      REAL MDOT,MDOTV,MDOTEV,MDOTCD,MDOTOG,MASRAT
      NAMELIST/ANS/ TIME,ALT, MDOT,TDOT,ZDOT, MDOTV, MDOTOG, MDOTEV,
     1 MDOTCD,VDOT,GALDOT,EM,TA,Z,EMV,EMOG,EMEV,EMCD,V,GAL,PR,PDOT,
     2PPAIR,PPFUEL,PPFLQS,UVENT,OF,MASRAT
C
C
 50   CALL EULER
      TIME=TIME+DT
      CALL DERIV
C
C
C
      RETURN
      END
```

```
      ELZ     = ELH*G/G0
      DMDZ    = 0.0
      EM      = WM0
C     CHECK TMS SLOPE AND CALCULATE PRESSURE
      IF (ELH .EQ. 0.0) GO TO 5
C     NON - ZERO SLOPE PRESSURE EQUATION
      A(4) = PM(J)*(TM(J)/TMS)**(GMRS/ELH)
      GO TO 9
C     ZERO SLOPE PRESSURE EQUATION
    5 A(4) = PM(J)*EXP(GMRS*(HG(J)-H)/TMS)
      GO TO 9
C     TMS LINEAR WITH Z. SEARCH MATRIX
    6 DO 7 I = 2,14
      J       = I + 8
      K       = I - 1
      IF (ZM(I) .GE. Z) GO TO 8
    7 CONTINUE
C     CALCULATE TMS, SLOPE, AND STUFF
    8 ELZ  = (TM(J+1) - TM(J))/(ZM(K+1) - ZM(K))
      TMS  = TM(J) + ELZ*(Z - ZM(K))
      DMDZ = (WM(K+1) - WM(K))/(ZM(K+1) - ZM(K))
      EM   = WM(K) + DMDZ*(Z - ZM(K))
      ZLZ  = Z - TMS/ELZ
C     PRESSURE EQUATION FOR TMS LINEAR WITH Z
      A(4) = PM(J)*EXP(GMRS/ELZ*(R0/(R0+ZLZ))**2*((Z-ZM(K))*
     1       (R0+ZLZ)/(R0+Z)/(R0+ZM(K)) - ALOG(TMS*(R0+ZM(K)
     2       )/TM(J)/(R0+Z))))
C     CALCULATE SOUND SPEED AND DERIVATIVE
    9 A(1) = 49.022164*SQRT(TMS)
      A(2) = 0.5*ELZ/TMS
C     CALCULATE DENSITY, DERIVATIVE, AND PRESSURE DERIVATIVE
      A(6) = GMRS*A(4)/G0/TMS
      A(7) = - (A(6)*G/A(4) + ELZ/TMS)
      A(5) = - A(6)*G
C     CALCULATE TEMPERATURE, DERIVATIVE, AND LEAVE
      A(8) = EM*TMS/WM0
      A(9) = (EM*ELZ + TMS*DMDZ)/WM0
   10 A8 = A(8)
      A4 = A(4)
      A1 = A(1)
      A6 = A(6)
      A5=A(5)
      RETURN
      END
```

```
      SUBROUTINE ATMOS(A3,A8,A4,A1,A6,A5)
C     THIS ROUTINE CALCULATES ATMOSPHERIC PROPERTIES OF THE
C     US STANDARD ATMOSPHERE,1962,ASSUMING AN INVERSE SQUARE
C     GRAVITATIONAL FIELD. THIS ASSUMPTION YIELDS DATA THAT
C     AGREES WITH THE COESA DOCUMENT WITHIN 1 PER CENT AT
C     ALL ALTITUDES UP TO 700 KILOMETERS (2296588 FEET). THE
C     DATA IS ARRANGED IN THE ATMOSPHERE ARRAY, A, AS
C     FOLLOWS
C     A(1)  = CS, SPEED OF SOUND, FT/SEC
C     A(2)  = (1/CS)(DCS/DZ), SOUND DERIVATIVE, 1/FT
C     A(3)  = Z, GEOMETRIC ALTITUDE, FT (GIVEN)
C     A(4)  = P, PRESSURE, LB/FT2
C     A(5)  = DP/DZ, PRESSURE DERIVATIVE, LB/FT3
C     A(6)  = RHO, DENSITY, SLUGS/FT3
C     A(7)  = (1/RHO)(DRHO/DZ), DENSITY DERIVATIVE, 1/FT
C     A(8)  = T, TEMPERATURE, DEG RANKINE
C     A(9)  = DT/DZ, TEMPERATURE DERIVATIVE, DEG RANKINE/FT
C     VARIOUS CONSTANTS USED
C      EARTH RADIUS                  = 20890855 FT
C      SPECIFIC HEAT RATIO FOR AIR = 1.4
C     SEA LEVEL VALUES
C      GRAVITATIONAL ACCELERATION  = 32.1740484 FT/SEC2
C      MOLECULAR WEIGHT              = 28.9644
C      G0*M0/R*                      = 0.018743418 DEG RANK/FT
      DIMENSION  A( 9),HG(10),ZM(14),WM(14),TM(23),PM(22)

C     SET ARRAYS AND CONSTANT VALUES
      DATA G0,WM0,R0,GMRS/32.1740484,28.9644,20890855.0,
     1     0.018743418/,HG/-16404.,0.0
     2     ,36089.,65617.,104987.,154199.,170604.,200131.,
     3     259186.,291160./,ZM/295276.,328084.,
     4     360892.,393701.,492126.,524934.,557743.,623360.,
     5     754593.,984252.,1312336.,1640420.,1968504.,
     6     2296588./,WM/28.9644,28.88,28.56,
     7     28.07,26.92,26.66,26.4,25.85,24.7,22.66,19.94,
     8     17.94,16.84,16.17/
      DATA TM/577.17,518.67,389.97,389.97,411.57
     1     ,487.17,487.17,454.77,325.17,325.17,379.17,469.17
     2     ,649.17,1729.17,1999.17,2179.17,2431.17,2791.17
     3     ,3295.17,3889.17,4357.17,4663.17,4861.17/,PM/
     4     3711.0839,2116.2165,472.67563,114.34314,
     5     18.128355,2.3162178,1.2321972,3.8030279E-01,
     6     2.1671352E-02,3.4313478E-03,6.2773411E-04,1.53490
     7     91E-04,5.2624212E-05,1.0561806E-05,7.7063076E-06,
     8     5.8267151E-06,3.5159854E-06,1.4520255E-06,3.92905
     9     63E-07,8.4030242E-08,2.2835256E-08,7.1875452E-09/
      A(3) = A3
C     CALCULATE G, Z, AND CHECK
    2 Z = A(3)
      G = G0*(R0/(R0+Z))**2
      IF (Z .GT. 295276.0) G  TO 6
C     TMS LINEAR WITH GEOPOTENTIAL. CALCULATE H AND SEARCH
      H      = R0*Z/(R0+Z)
      DO 3 I = 2,10
      J      = I - 1
      IF (HG(I) .GE. H) GO TO 4
    3 CONTINUE
C     CALCULATE TMS SLOPE,TMS, AND SET MOL WT STUFF
    4 ELH    = (TM(J+1) - TM(J))/(HG(J+1) - HG(J))
      TMS    = TM(J) +  ELH*(H - HG(J))
```

```
      A(2,1) = 1./EM
      A(2,2) = 1./TA
      A(2,3) = EMW*(1./EMWA - 1./EMWF)
      A(2,4) = 0.0
      A(3,1) = 1./EM
      A(3,2) = 1./TA
      A(3,3)=(GAMMA/CP)*(CPA-CPF-RGAS*(1./EMWA-1./EMWF))
      A(3,4) = -CPV*TV/E
      A(4,1) = 1.0
      A(4,2) = 0.0
      A(4,3) = 0.0
      A(4,4) = -1.0
      Y(1) =  MDOTOG*ZOG/EM
      Y(2) = PDOT/PR+ VDOT/V
      HTRANS = 0.
      DO 300 I= 1,3
  300 HTRANS = HTRANS + HJ(I)*AJ(I)*(TJ(I) - TA)
      Y(3) = ( MDOTEV*CPF*TF +  MDOTOG*CPOG*TF -  MDOTCD*(CPF*TA-
     1 DELHF) + HTRANS)/E
      Y(4) =  MDOTEV +  MDOTOG -  MDOTCD
C
C
      CALL LESK (C,X,DUMMY,4,1,4,0,LA)
      IF(MDOTV .EQ. 0.) GO TO 375
      IF( MDOTVL/MDOTV) 350,350,375
  350 NCYC = NCYC +1
      IF  (NCYC .LE. 10) GO TO 140
      WRITE(6,900)
      STOP
  375 IF (LA.EQ.0) GO TO 400
      WRITE (6,800)
      STOP
  400 CONTINUE
  800 FORMAT (30HCOEFFICIENT MATRIX IS SINGULAR)
  900 FORMAT(30HVENTING CALCULATION IS CYCLING)
      RETURN
      END
```

```
   75 TJ(1) = LIN( M(1),4)
      TJ(2) = LIN( M(1),3)
      TJ(3) = LIN( M(1),2)
      PVAP  = LIN( TF,7)
      DO 100 I = 1,3
  100 TJ(I) = TJ(I)  + 459.7
C
C   CALCULATE  MDOTOG, MDOTCD, MDOTEV
C
       MDOTCD =0.0
      RHORT  = PR*EMW
      PPAIR  = Z*RHORT/EMWA
      PPFUEL = PR - PPAIR
      PPFLQS = PVAP*144.
      IF(PPFLQS .GE. 0.99*PR) GO TO 120
       MDOTEV =0.0
      PPALQS = PR - PPFLQS
      IF(ABS(PPAIR-PPALQS).LT.1.E-10) GO TO 130
      PAM = (PPAIR - PPALQS)/ALOG(PPAIR/PPALQS)
      CKG = DV*PR/(RGAS*TA*PAM*CDELTA)
       MDOTEV =AJ(3)*CKG*(PPFLQS - PPFUEL)*EMWF
      GO TO 130
  120 WRITE(6,65)
   65 FORMAT(////28HFUEL BOILING MDOTEV CONSTANT)
C    TEMPORARY CALCULATION OF AMOUNT OF DISOLVEDGAS
  130 EMWOG = EMWA
      VLIQ = (GALO-GAL)*231./1728.
      EMDISE = (BETA*EMWOG*VLIQ *PPAIR)/(.797*453.*2116.224)
      EMDIS = EMDISO - EMOG - SUMMDO
      IF(EMDIS .LT. 0. ) WRITE(6,55)
   55 FORMAT(*0AMOUNT OF DISSOLVED GAS IS NEGATIVE*)
      CON = CON1
      IF((EMDIS-EMDISE) .LT. 0. ) CON = CON2
      MDOTOG = CON*(EMDIS-EMDISE)
      EMDOOT = EMDIS*GALOOT*231./VLIQ/1728.
      IF( TIME .EQ. TO ) MDOTV = PDOT
  140 IF(MDOTV .GE. 0.0) GO TO 150
C
C     VENTING
C
      CPV = CP
      TV  = TA
      ZV  =  Z
      EMWV = EMW
      GO TO 200
C
C     FILLING
C
  150 CPV= CPA
      TV=   TALT*(1.+ SQRT(0.72)*0.2*AMACH**2)
      IF(TVENT .GT. 0.) TV = TVENT
      ZV = 1.0
      EMWV = EMWA
  200 RHOV = PR*EMWV/(RGAS*TV)
      MDOTVL = MDOTV
C
      A(1,1) = Z/EM
      A(1,2) = 0.0
      A(1,3) = 1.0
      A(1,4) = -ZV/EM
```

```
      SUBROUTINE DERIV
      COMMON/LIMITS/TO,TMAX,DT,TPRNT,DTPRNT,TIME,M16
      COMMON/STIR/ RGAS,EMWA,EMWF,CPA,CPF,HJ(3),ULLGH,ULWID,ULHT,
     1DELHF,ZOG,AV,CP,EMW,DV,CDELTA,KTANK,GALO,TVENT
      COMMON/EULIN/ MDOT,TDOT,ZDOT, MDOTV, MDOTOG, MDOTEV, MDOTCD,VDOT,
     1GALDOT,
     2EM,TA,Z,EMV,EMOG,EMEV,EMCD,V,GAL
      COMMON/ETC/ ALT,AJ(3),TJ(3),RHOV,PR,PPAIR,PPFUEL,PPFLGS,
     1 AMACH,DALTDT,PDOT,OF,MASRAT,UVENT
      COMMON/OUTGAS/BETA,CON1,CON2,RHOLIQ,EMDISO,SUMMDO,EMDDOT
     1,VLIQ,EMDIS,EMDISE
      REAL LIN,M(1)
      REAL MDOT,MDOTV,MDOTEV,MDOTCD,MDOTOG,MDOTVL
      DIMENSION A(4,4),Y(4),C(4,5),X(4),DUMMY(4)
      EQUIVALENCE (A,C), (Y,C(17)), (X, MDOT), (TJ(3),TF)

      NAMELIST/QED/ PPALGS,AJ,TJ,RHOV,CP,DALTDT,CPV,TV,ZV,EMWV,Z,ZDOT
      NAMELIST/COEF/A,Y,HTRANS




      NCYC = 1
      M(1)= TIME
      AMACH = LIN(M(1),8)
      CP = (1.-Z)*CPF + Z*CPA
      EMW = 1./( Z/EMWA  + (1.-Z)/EMWF )
      GAMMA = 1./(1.-RGAS/(EMW*CP*778.))
      E = EM*CP*TA/GAMMA
      CPOG = (1. - ZOG)*CPF  + ZOG*CPA
      ALT = LIN(M(1),5)
      ALT = ALT*1000.0
      DELT=  DT
      IF( TIME +DT .GE. TMAX ) DELT =-DT
      TPDELT = TIME +DELT
      ALT1  = LIN( TPDELT,5 )
      ALT1 = ALT1*1000.0
      DALTDT = (ALT1 - ALT)/DELT
      CALL ATMOS (ALT,TALT,PR,DUMM,DUM1,DPDALT)
      PDOT = DPDALT*DALTDT
      GALDOT = LIN( M(1),6)
      VDOT  = GALDOT*231./1728.
      IF( KTANK .EQ. 1) GO TO 50
C
C              RECTANGULAR TANK
C CALC AJ S , TJ S   1= TOP , 2= 4 SIDES , 3= FUEL SURFACE
C
      ULHT = V/(ULWID*ULLGH)
      AJ(1) = ULWID*ULLGH
      AJ(2) =2.*ULHT*(ULWID + ULLGH)
      AJ(3) = AJ(1)
      GO TO 75
C
C           CYLINDRICAL TANK - AXIS HORIZONTAL
C   1 = TOP, 2 = 2 CIRCULAR SIDES, 3 = FUEL SURFACE,   DIAMETER =  ULWID
C
   50 GALNOW = (GALO - GAL) * 231./1728.
      THET = 8.*GALNOW/( ULWID**2*ULLGH)
      AJ(1) = (3.14159265 - THET/2.)* ULWID*ULLGH
      AJ(2) =  ULWID**2*THET/4.
      AJ(3) =  ULWID*ULLGH*SIN(THET/2.)
C
```

```
 74   CONTINUE
 75   CONTINUE
      CALL INITIL
      CALL DERIV
      CALL PRINT
C
C          ENTER INTEGRATION LOOP
C
      M16= 0
 100  M16= M16+1
      CALL FUNCT
      IF( IPRT .EQ. 0) GO TO 200
C
C          LAST TIME STEP WAS TO PRINT STATION
C
 150  TIME= TPRNT
      CALL PRINT
      TPRNT= TPRNT + DTPRNT
      IF(TIME.GE.TMAX) GO TO 1001
      DT= DTSV
      IPRT=0
 200  CONTINUE
C          CHECK FOR PRINT STATION
C
      CK= TIME + DT+  TOL
      IF(TIME.GT.TMAX) GO TO 1001
      IF( CK .GT. TMAX) TPRNT=TMAX
      IF(  CK .LT. TPRNT) GO TO 100
      IPRT=1
      DTSV= DT
      DT= TPRNT- TIME
      IF( DT .LE. TOL) GO TO 150
      GO TO 100
1000  STOP
1001  GALX=GALO
      WRITE(7)(FAR(I),I=1,1253)
      GO TO 50
      END
```

```
      SUBROUTINE PRINT
      COMMON/TITL/CID(12)
      COMMON/LIMITS/TO,TMAX,DT,TPRNT,DTPRNT,TIME,M16
      COMMON/STIR/ RGAS,EMWA,EMWF,CPA,CPF,HJ(3),ULLGH,ULWID,ULHT,
     1DELHF,ZOG,AV,CP,EMW,DV,CDELTA,KTANK,GALO,TVENT
      COMMON/EULIN/ MDOT,TDOT,ZDOT, MDOTV, MDOTOG, MDOTEV, MDOTCD,VDOT,
     1GALDOT,
     2EM,TA,Z,EMV,EMOG,EMEV,EMCD,V,GAL
      COMMON/ETC/ ALT,AJ(3),TJ(3),RHOV,PR,PPAIR,PPFUEL,PPFLQS,
     1 AMACH,DALTDT,PDOT,OF,MASRAT,UVENT
      COMMON/OUTGAS/BETA,CON1,CON2,RHOL10,EMDISO,SUMMDO,EMDDOT
     1,VLIQ,EMDIS,EMDISE
      COMMON /FILE7/ FAR(250),FLEFT(250),FTEMP(250),HT(250),VT(250),
     1ITPRNT,GALX,TINC
      REAL M(1)
      REAL MDOT,MDOTV,MDOTEV,MDOTCD,MDOTOG,MASRAT
C
C
      M(1)= TIME
      UVENT =  MDOTV/(RHOV*AV)
      OF = Z/(1.-Z)
      EM1 = PR*V*EMW/(RGAS*TA)
      MASRAT= (1.-EM1/EM)*100.
      WRITE(6,100)(CID(I),I=1,12)
      WRITE(6,500) M(1),PPAIR,AMACH,PPFUEL,UVENT,PPFLQS,MASRAT,OF
      WRITE(6,600) ALT,DALTDT,PR,PDOT,TA,TDOT,V,VDOT,GAL,GALDOT
      WRITE(6,700)EMV,MDOTV,EMEV,MDOTEV,EMOG,MDOTOG,EMCD,MDOTCD,EM,MDOT
      ITPRNT=ITPRNT+1
      FAR(ITPRNT)=1.0/OF
      FLEFT(ITPRNT)=100.0*(1.0-GAL/GALO)
      FTEMP(ITPRNT)=TJ(3)-459.7
      HT(ITPRNT)=ALT
      VT(ITPRNT)=AMACH
C
  100 FORMAT(1H1///33X,12A6///////)
  500 FORMAT(20X,20H        TIME        =,    G13.5,27X,23HAIR PARTIAL PRE
     1SSURE  =,E13.5//
     2        20X,20H    MACH NUMBER     =,    G13.5,27X,23HFUEL PARTIAL PR
     3ESSURE =,E13.5//
     4        20X,20H    VENT VELOCITY   =,    G13.5,27X,23HFUEL VAPOR PRES
     5SURE   =,E13.5//
     6        20X,20HINTEGRATION ERROR   =,    G13.5,27X,23H   AIR-FUEL RAT
     7IO      =,E13.5/
     8        20X,18HTOTAL MASS-PERCENT)
C
  600 FORMAT(//65X,5HVALUE,16X,10HDERIVATIVE//
     1 39X,12H  ALTITUDE   ,10X,E13.5,10X,E13.5/
     2 39X,12H  PRESSURE   ,10X,E13.5,10X,E13.5/
     3 39X,12HTEMPERATURE  ,10X,E13.5,10X,E13.5/
     4 39X,12H   VOLUME    ,10X,E13.5,10X,E13.5/
     5 39X,12HGALLONS USED,10X,E13.5,10X,E13.5)
C
  700 FORMAT(//64X,4HMASS,19X,9HMASS FLUX//
     1 40X,10H  VENTED   ,10X,E13.5,10X,E13.5/
     2 40X,10HEVAPORATED,10X,E13.5,10X,E13.5/
     3 40X,10HOUTGASSED  ,10X,E13.5,10X,E13.5/
     4 40X,10HCONDENSED  ,10X,E13.5,10X,E13.5/
     5 40X,10H  TOTAL    ,10X,E13.5,10X,E13.5)
       NAMELIST/OGAS/EMDISO,SUMMDO,EMDDOT,VLIQ,EMDIS,EMDISE
       RETURN
```

INPUT DATA FOR WSFT B-1 FORWARD FUSELAGE TANK TEST CASE

```
9  END OF RECORD
9  END OF RECORD
          TEST CASE FOR [redacted] FUSELAGE TANK
 $DATA
 RGAS=1545,
 EMWA=28.966,EMWF=72,
 CPA=0.24,CPF=0.49,
 TA=60,
 HJ=3$2,
 ULLGH=10.0,ULWID=10.0,ULHT=0.55,
 DELHF=1,
 ZOG=1,
 AV=0.16,
 DV=0.3,
 CDELTA=0.01,
 KTANK=0,
 GALO=5573,
 BETA=0.16,
 CON1=1000,CON2=0,
 TVENT=70,
 TF(1,1)=0,1,2,3,4,5,6,7,8,9,10,11,12,
 TF(1,2)=60,60,58,48,48,45,15,18,20,25,110,130,120,
 TSIDE(1,1)=0,12,TSIDE(1,2)=70,70,
 TTOP(1,1)=0,12,TTOP(1,2)=70,70,
 ALT(1,1)=0,.1,.3,.5,1,4,5,6,8,8.3,12,
 ALT(1,2)=0,8,20,22,22,20,18,20,22,.25,.25,
 GALDOT(1,1)=0,8.3,8.31,10.3,10.31,12,
 GALDOT(1,2)=0,0,2779,2779,0,0,
 PVAP(1,1)=17,41,67,96,129,166,PVAP(1,2)=.35,.60,1.1,2.0,4.0,8.0,
 EMINF(1,1)=0,.5,12 ,EMINF(1,2)=0,.85,.85,
 TO=0,TMAX=11,DTPRNT=.25,DT=.001$
9  END OF RECORD
9
```

PATH TAPE CREATOR PROGRAM

```
FV1,CM100000,T20,I0100,P6.
FV1,CM100000,T20,I0100,P6.
ATTACH(TAPE7,TNK1)
REQUEST,TAPE6,*PF.
FTN(R=3)
LGO.
CATALOG(TAPE6,B1A,RP=999,RN=1)
9
      PROGRAM MAIN(INPUT,OUTPUT,TAPE5=INPUT,TAPE6,TAPE7,TAPE8,TAPE9,
     1TAPE10,TAPE11,TAPE12,TAPE13,TAPE14,TAPE15,TAPE16)
      COMMON /SAVE/ HT(250),VT(250),FAR(250,10),FLEFT(250,10),
     1FTEMP(250,10),GAL(10),NTANKS,NTPO,TINC
      COMMON /FILE7/ FA(250),FL(250),FT(250),H(250),V(250),NTP,GALX,TIN
      INTEGER GAL
      READ(5,1000)NTANKS
      READ(7)(FA(I),I=1,1253)
      DO 1 I=1,NTP
      HT(I)=H(I)
      VT(I)=V(I)
      FAR(I,1)=FA(I)
      FTEMP(I,1)=FT(I)
    1 FLEFT(I,1)=FL(I)
      NT=NTP
      NTPO=NTP
      TINC=TIN
      GAL(1)=GALX
      IF(NTANKS.EQ.1) GO TO 4
      IEND=6+NTANKS
      DO 3 I=8,IEND
      K=I-6
      READ(I)(FA(J),J=1,1253)
      IF(NT.NE.NTP) GO TO 5
      DO 2 J=1,NTP
      IF(HT(J).NE.H(J)) GO TO 5
      IF(VT(J).NE.V(J)) GO TO 5
      FAR(J,K)=FA(J)
      FTEMP(J,K)=FT(J)
    2 FLEFT(J,K)=FL(J)
    3 GAL(K)=GALX
    4 WRITE(6)(HT(I),I=1,8013)
      STOP
    5 PRINT 2000
      STOP
 1000 (ORMAT(I5)
 2000 (ORMAT(* DI((ERENT (LIGHT PRO(ILES (OR TWO TANKS*)
      END
9
    1
9
9
```

VULNERABILITY PROGRAM

```
FVM,CM60000,T600,10100,P2.
FTN(R=3,B=FVMAD)
ATTACH(TAPE6,F4D)
FVMAD.
9
      PROGRAM FVMN(INPUT,OUTPUT,TAPE6)
      COMMON /COUNTER/ VSCUM(10),RSCUM(10),IHIT(10),IEF(10),IAFEN(10),
     1IAFEXA(10),IAFEXB(10),IRAM(10),IFE(10),ILEAK(10)
      COMMON /WEAPONS/ VZERO(32),PENM(32),CDRAG(32),ISORF(32),AZMIN(32),
     1AZMAX(32),ELMIN(32),ELMAX(32),NSHOTS(32),TIGN(32),TASH(32),IHE(32)
      COMMON /TANKS/ DSKIN(6,10),IIG(6,10),XCG(10),YCG(10),ZCG(10),
     1X1(10),Y1(10),Z1(10),X2(10),Y2(10),Z2(10),HMIN(10),FULLPC(10)
      COMMON /INOUT/ A,B,C,IASP,JASP,XIN,YIN,ZIN,XOUT,YOUT,ZOUT,ENTRY,
     1AFEN,AFEX,XO,YO,ZO
      COMMON /PROFILE/ H(250),AMACH(250),FAR(250,10),PFUEL(250,10),
     1FTEMP(250,10),GAL(10),NTANKS,NTP,TINC
      COMMON /ALPHA/ ATANK(2,10),AWEAP(32),AWAR(2),ASOL(2),ATARG
      COMMON /MILERRS/ EMIL(32,32)
      COMMON /FRAGS/ VE(32),PSI(32),COSMAX(32),COSMIN(32),CD(32),SF(32),
     1XF(32),YF(32),ZF(32)
      DIMENSION CEF(10),CFE(10),CLEAK(10),PHCUM(10),PAF(10),PBF(10)
      EQUIVALENCE(CEF(1),IEF(1)),(CFE(1),IFE(1)),(CLEAK(1),ILEAK(1)),
     1(PHCUM(1),IAFEXA(1))
      LOGICAL ENTRY,NOHE,AFEN,AFEX
      INTEGER GAL,XST,WEAPS(250)
      DATA TWOPI,DTOR,GEE/6.28318531,0.017453293,32.172/
      DATA AWAR,ASOL/10HFRAGMENTIN,10HG WARHEAD ,10H SOLID SHO,10HT WEAP
     1ON  /
      CALL REPT1
      READ 2000,NWEAPS,XST,HRAM,RATMIN,RATMAX
      READ 2001,(WEAPS(I),I=1,NTP)
      READ 2002,(ISORF(I),IHE(I),NSHOTS(I),AZMIN(I),AZMAX(I),ELMIN(I),
     1ELMAX(I),XF(I),YF(I),ZF(I),I=1,NWEAPS)
      READ 2003,(TIGN(I),TASH(I),VZERO(I),PENM(I),CDRAG(I),I=1,NWEAPS)
      READ 2007,(VE(I),PSI(I),COSMAX(I),COSMIN(I),CD(I),SF(I),
     1I=1,NWEAPS)
      READ 2004,((EMIL(I,J),I=1,32),J=1,NWEAPS)
      READ 2005,((IIG(I,J),I=1,6),(DSKIN(I,J),I=1,6),J=1,NTANKS)
      READ 2006,(XCG(I),YCG(I),ZCG(I),HMIN(I),FULLPC(I),I=1,NTANKS)
      READ 2007,(X1(I),Y1(I),Z1(I),X2(I),Y2(I),Z2(I),I=1,NTANKS)
      READ 2008,(AWEAP(I),I=1,NWEAPS)
      DO 103 ITIME=1,NTP
      TIM=TINC*(ITIME-1)
      VT=DEMACH(AMACH(ITIME),H(ITIME))
      DELTA=0.5/VT
      ALT=H(ITIME)
      DO 102 IWEAP=1,NWEAPS
      IF(AND(WEAPS(ITIME),2**(IWEAP-1)).NE.2**(IWEAP-1)) GO TO 102
      SLUGS=PENM(IWEAP)/(7000.0*GEE)
      VEM=VE(IWEAP)
      BB=CD(IWEAP)
      COSTMX=COSMAX(IWEAP)
      COSTMN=COSMIN(IWEAP)
      PSIST=PSI(IWEAP)
      FM=PENM(IWEAP)
      SIGF=SF(IWEAP)
      XFUSE=XF(IWEAP)
      YFUSE=YF(IWEAP)
      ZFUSE=ZF(IWEAP)
      T1=TIGN(IWEAP)
```

```
      T2=TASH(IWEAP)
      IVT=VT
      I=IVT/100+1
      IF(I.GT.30) GO TO 1
      ERR=EMIL(I,IWEAP)+(0.01*VT-I+1.0)*(EMIL(I+1,IWEAP)-EMIL(I,IWEAP))
      GO TO 2
    1 ERR=EMIL(I,IWEAP)
    2 NOHE=.TRUE.
      IF(IHE(IWEAP).GT.0) NOHE=.FALSE.
      NSH=NSHOTS(IWEAP)
      DO 500 I=1,100
  500 VSCUM(I)=0.0
      DO 100 ISHOT=1,NSH
      AZ=AZMIN(IWEAP)+RANF(XST)*(AZMAX(IWEAP)-AZMIN(IWEAP))
      EL=ELMIN(IWEAP)+RANF(XST)*(ELMAX(IWEAP)-ELMIN(IWEAP))
      AZ=AZ*DTOR
      EL=EL*DTOR
      COSE=COS(EL)
      XMU=-COSE*COS(AZ)
      YMU=-COSE*SIN(AZ)
      ZMU=SIN(EL)
      RS=ABS(ALT/ZMU)
      IF(ISORF(IWEAP).GT.1) GO TO 3
      SIGMA=RS*ERR*0.001/0.6745
      GO TO 4
    3 SIGMA=ERR
    4 DM=ABS(GAUS(SIGMA))
      THETA=RANF(XST)*TWOPI
      COSTH=COS(THETA)
      SINTH=SIN(THETA)
      VSH=VZERO(IWEAP)*EXP(-RS*CDRAG(IWEAP))
      AA=VEM/VSH
      VR=SQRT(VSH*VSH+VT*VT-2.0*VSH*VT*XMU)
      A=(VSH*XMU-VT)/VR
      B=VSH*YMU/VR
      C=1.0-A*A-B*B
      IF(C)5,6,7
    5 B=SIGN(SQRT(1.0-A*A),YMU)
    6 C=0.0
      GO TO 8
    7 C=SIGN(SQRT(C),ZMU)
      IF(ABS(C).EQ.1.0) GO TO 9
      D=SQRT(A*A+B*B)
      COSPSI=-A/D
      SINPSI=B/D
      XO=DM*(C*COSTH*COSPSI+SINTH*SINPSI)
      YO=DM*(-C*COSTH*SINPSI+SINTH*COSPSI)
      ZO=(-A*XO-B*YO)/C
      GO TO 10
    8 XO=DM*B*SINTH
      YO=-DM*A*SINTH
      ZO=DM*COSTH
      GO TO 10
    9 XO=DM*COSTH
      YO=DM*SINTH
      ZO=0.0
   10 IF(ISORF(IWEAP).GT.1) GO TO 50
      ENTRY=.FALSE.
      DO 11 ITANK=1,NTANKS
      CALL IN(XCG(ITANK),YCG(ITANK),ZCG(ITANK),X1(ITANK),Y1(ITANK),
```

```
     1Z1(ITANK),0.01*PFUEL(ITIME,ITANK)*FULLPC(ITANK))
      IF(.NOT.ENTRY) GO TO 11
      CALL OUT(XCG(ITANK),YCG(ITANK),ZCG(ITANK),X1(ITANK),Y1(ITANK),
     1Z1(ITANK),0.01*PFUEL(ITIME,ITANK)*FULLPC(ITANK))
      GO TO 14
   11 CONTINUE
      IF(NOHE) GO TO 100
      DO 12 ITANK=1,NTANKS
      CALL IN(XCG(ITANK),YCG(ITANK),ZCG(ITANK),X2(ITANK),Y2(ITANK),
     1Z2(ITANK),-1.0)
      IF(.NOT.ENTRY) GO TO 12
      ILEAK(ITANK)=ILEAK(ITANK)+1
      IHIT(ITANK)=IHIT(ITANK)+1
      IF(I1G(IASP,ITANK).GT.0) IEF(ITANK)=IEF(ITANK)+1
   12 CONTINUE
      GO TO 100
   14 IHIT(ITANK)=IHIT(ITANK)+1
      RATIO=FAR(ITIME,ITANK)
      RSCUM(ITANK)=RSCUM(ITANK)+RS
      VSCUM(ITANK)=VSCUM(ITANK)+VSH
      ENERGY=0.5*SLUGS*VSH*VSH
      D1=DSKIN(IASP,ITANK)
      IF(ENERGY.LT.HMIN(ITANK)) GO TO 100
      IF(AFEN) GO TO 23
      IF(ENERGY.LT.HRAM) GO TO 15
      IRAM(ITANK)=IRAM(ITANK)+1
      GO TO 100
   15 IF(AFEX) GO TO 17
      ILEAK(ITANK)=ILEAK(ITANK)+1
      IF(I1G(JASP,ITANK).GT.0) GO TO 16
  200 IF(I1G(IASP,ITANK).GT.0) GO TO 16
      IF(VSH*T1.GT.D1) GO TO 100
      IF(VSH*T2.LT.D1) GO TO 100
   16 IEF(ITANK)=IEF(ITANK)+1
      GO TO 100
   17 IAFEXB(ITANK)=IAFEXB(ITANK)+1
      IF(RATIO.LT.RATMIN) GO TO 22
      IF(RATIO.GT.RATMAX) GO TO 22
      GO TO (18,18,19,19,20,20),IASP
   18 D2=D1+2.0*X1(ITANK)
      GO TO 21
   19 D2=D1+2.0*Y1(ITANK)
      GO TO 21
   20 D2=D1+2.0*Z1(ITANK)
   21 IF(VSH*T1.GT.D2) GO TO 22
      IF(VSH*T2.LT.D1) GO TO 22
      IFE(ITANK)=IFE(ITANK)+1
      GO TO 100
   22 ILEAK(ITANK)=ILEAK(ITANK)+1
      GO TO 200
   23 IAFEN(ITANK)=IAFEN(ITANK)+1
      IF(RATIO.LT.RATMIN) GO TO 28
      IF(RATIO.GT.RATMAX) GO TO 28
      GO TO (24,24,25,25,26,26),IASP
   24 D2=D1+2.0*X1(ITANK)
      GO TO 27
   25 D2=D1+2.0*Y1(ITANK)
      GO TO 27
   26 D2=D1+2.0*Z1(ITANK)
   27 IF(VSH*T1.GT.D2) GO TO 28
```

```
      IF(VSH*T2.LT.U1) GO TO 28
      IFE(ITANK)=IFE(ITANK)+1
      IF(AFEX) IAFEXA(ITANK)=IAFEXA(ITANK)+1
      GO TO 100
   28 IF(.NOT.AFEX) GO TO 29
      IAFEXA(ITANK)=IAFEXA(ITANK)+1
      GO TO 100
   29 IF(ENERGY.LT.HRAM) GO TO 30
      IRAM(ITANK)=IRAM(ITANK)+1
      GO TO 100
   30 ILEAK(ITANK)=ILEAK(ITANK)+1
      IF(IIG(JASP,ITANK).GT.0) IEF(ITANK)=IEF(ITANK)+1
      GO TO 100
   50 TF=GAUS(SIGF)/VSH
      XSTAR=XO+TF*(VSH*XMU-VT)+XFUSE
      YSTAR=YO+TF*VSH*YMU+YFUSE
      ZSTAR=ZO+TF*VSH*ZMU+ZFUZE
      DO 61 ITANK=1,NTANKS
      YT=YCG(ITANK)-YSTAR
      ZT=ZCG(ITANK)-ZSTAR
      XTT=XCG(ITANK)-XSTAR
      C1=VR*VR-VEM*VEM
      C2=VSH*((XMU-VT/VSH)*XTT+YMU*YT+ZMU*ZT)/C1
      C3=XTT*XTT+YT*YT+ZT*ZT
      DISCR=SQRT(C2*C2-C3/C1)
      T=C2-DISCR
      IF(T.LT.0.0) T=C2+DISCR
      ITER=0
   51 IF(ITER.GT.25) GO TO 61
      XT=XTT+VT*T
      XL=SQRT(XT*XT+YT*YT+ZT*ZT)
      IF(XL.EQ.0.0) GO TO 61
      BETAX=XT/XL
      BETAY=YT/XL
      BETAZ=ZT/XL
      COSGAM=XMU*BETAX+YMU*BETAY+ZMU*BETAZ
      VO=VSH*COSGAM+SQRT(VSH*VSH*COSGAM*COSGAM+VEM*VEM-VSH*VSH)
      VODOT=VO*VSH*VT*(XMU-BETAX*COSGAM)/(XL*(VO-VSH*COSGAM))
      FDOT=BB*((VO+VODOT*T)/(1.0+BB*VO*T)-BETAX*VT)
      IF(FDOT.LE.0.0) GO TO 61
      F=ALOG(1.0+BB*VO*T)-BB*XL
      TNEW=T-F/FDOT
      IF(ABS(TNEW-T).LE.DELTA) GO TO 52
      T=TNEW
      ITER=ITER+1
      GO TO 51
   52 IF(XL.GT.500) GO TO 61
      COSTH=(VO*COSGAM-VSH)/VEM
      IF(COSTH.LT.COSTMX) GO TO 61
      IF(COSTH.GT.COSTMN) GO TO 61
      IHIT(ITANK)=IHIT(ITANK)+1
      E=AA*AA*ABS(AA+COSTH)/(AA*AA+2.0*AA*COSTH+1.0)**1.5
      PSIC=PSIST/(E*XL*XL)
      VHIT=VO*EXP(-BB*XL)
      VNET=SQRT(VHIT*VHIT-2.0*VT*VHIT*BETAX+VT*VT)
      EDENS=0.5*SLUGS*VNET*VNET*PSIC
      IF(EDENS.GE.HRAM) IRAM(ITANK)=IRAM(ITANK)+1
      ATB=4.0*X1(ITANK)*Y1(ITANK)
      ASS=4.0*X1(ITANK)*Z1(ITANK)
      AFR=4.0*Y1(ITANK)*Z1(ITANK)
```

```
      SAR=ABS(BETAX)*AFR+ABS(BETAY)*ASS
      TAR=SAR+ABS(BETAZ)*ATB
      PHCUM(ITANK)=PHCUM(ITANK)+1.0-EXP(-PSIC*TAR)
      ARBF=0.01*PFUEL(ITIME,ITANK)*0.01*FULLPC(ITANK)*SAR
      ARAF=SAR-ARBF
      IF(BETAZ)53,55,54
   53 ARAF=ARAF-BETAZ*ATB
      GO TO 55
   54 ARBF=ARBF+BETAZ*ATB
   55 PHITBF=1.0-EXP(-PSIC*ARBF)
      PHITAF=1.0-EXP(-PSIC*ARAF)
      TMP=FTEMP(ITIME,ITANK)
      IF(ALT.LT.10000.0) GO TO 56
      AFAC=2.5*EXP(-.000092*ALT)
      IF(ALT.GT.60000.0) GO TO 58
      IF(TMP.LT.0.0) GO TO 58
      IF(TMP.GT.45.0) GO TO 57
      DF=TMP/45.0*(1.2-0.00002*ALT)
      GO TO 60
   56 AFAC=1.0
      IF(TMP.LT.0.0) GO TO 58
      IF(TMP.GT.45.0) GO TO 59
      DF=TMP/45.0
      GO TO 60
   57 DF=1.2-0.00002*ALT
      GO TO 60
   58 DF=0.0
      GO TO 60
   59 DF=1.0
   60 CEF(ITANK)=CEF(ITANK)+0.3*DF*PHITBF
      CLEAK(ITANK)=CLEAK(ITANK)+PHITBF*(1.0-0.3*DF)
      RATIO=FAR(ITIME,ITANK)
      IF(RATIO.LT.RATMIN) GO TO 62
      IF(RATIO.GT.RATMAX) GO TO 62
      CFE(ITANK)=CFE(ITANK)+.00000769*SQRT(FM)*VNET*AFAC*PHITAF
   62 VSCUM(ITANK)=VSCUM(ITANK)+VNET
      RSCUM(ITANK)=RSCUM(ITANK)+RS
   61 CONTINUE
  100 CONTINUE
      IF(ISORF(IWEAP).GT.1) GO TO 108
      DO 101 ITANK=1,NTANKS
      IF(IHIT(ITANK).EQ.0) GO TO 101
      VSAVE=VSCUM(ITANK)/IHIT(ITANK)
      PAFEN=(1.0*IAFEN(ITANK))/IHIT(ITANK)
      IF(IAFEN(ITANK).EQ.0) GO TO 104
      PAFEXA=(1.0*IAFEXA(ITANK))/IAFEN(ITANK)
      GO TO 105
  104 PAFEXA=0.0
      PAFEXB=(1.0*IAFEXB(ITANK))/IHIT(ITANK)
      GO TO 107
  105 IF(IAFEN(ITANK).EQ.IHIT(ITANK)) GO TO 106
      PAFEXB=(1.0*IAFEXB(ITANK))/(IHIT(ITANK)-IAFEN(ITANK))
      GO TO 107
  106 PAFEXB=0.0
  107 PLEAK=(1.0*ILEAK(ITANK)-IEF(ITANK))/IHIT(ITANK)
      PFE=(1.0*IFE(ITANK))/IHIT(ITANK)
      PEF=(1.0*IEF(ITANK))/IHIT(ITANK)
      RSAVE=RSCUM(ITANK)/IHIT(ITANK)
      PHIT=(1.0*IHIT(ITANK))/NSH
      PRAM=(1.0*IRAM(ITANK))/IHIT(ITANK)
```

```
      PNOEF=1.0-PLEAK-PRAM-PFE-PEF
      PBFEN=1.0-PAFEN
      PBFEXA=1.0-PAFEXA
      PBFEXB=1.0-PAFEXB
      PRINT 1000,ASOL,ATARG,(ATANK(I,ITANK),I=1,2)
      PRINT 1001,TIM,AWEAP(IWEAP),PBFEN
      PRINT 1002,PHIT,PFUEL(ITIME,ITANK)
      PRINT 1003,VSAVE,FTEMP(ITIME,ITANK),PBFEXB
      PRINT 1004,RSAVE,FAR(ITIME,ITANK),PAFEXB
      PRINT 1005,H(ITIME),VT,PAFEN
      PRINT 1006,PBFEXA,PAFEXA
      PRINT 1007,PNOEF,PLEAK,PEF,PRAM,PFE
  101 CONTINUE
      GO TO 102
  108 DO 109 ITANK=1,NTANKS
      IF(PHCUM(ITANK).EQ.0.0) GO TO 109
      VSAVE=VSCUM(ITANK)/IHIT(ITANK)
      PLEAK=CLEAK(ITANK)/IHIT(ITANK)
      PFE=CFE(ITANK)/IHIT(ITANK)
      PEF=CEF(ITANK)/IHIT(ITANK)
      RSAVE=RSCUM(ITANK)/IHIT(ITANK)
      PHIT=PHCUM(ITANK)/NSH
      PRAM=(1.0*IRAM(ITANK))/IHIT(ITANK)
      PRINT 1000,AWAR,ATARG,(ATANK(I,ITANK),I=1,2)
      PRINT 1013,TIM,AWEAP(IWEAP)
      PRINT 1008,PHIT,PFUEL(ITIME,ITANK)
      PRINT 1009,VSAVE,FTEMP(ITIME,ITANK)
      PRINT 1010,SIGMA,FAR(ITIME,ITANK)
      PRINT 1011,ALT,VT
      PRINT 1012,PLEAK,PEF,PRAM,PFE
  109 CONTINUE
  102 CONTINUE
  103 CONTINUE
      STOP
 1000 (ORMAT(*1*,51X,*(UEL TANK VULNERABILITY MODEL*/62X,*REPORT 2*/*0*,
     155X,2A10/*0*,49X,*VEHICLE--*,A10/*0*,49X,*FUEL TANK--*,2A10)
 1001 (ORMAT(*0TIME INTO MISSION(HRS)--*,(7.3,18X,*THREAT--*,A10,21X,
     1*PROBABILITY OF LIQUID ENTRY--*,F9.6)
 1002 (ORMAT(*0PROBABILITY O( HIT ON (UEL TANK--*,(9.6,7X,*PERCENT (UEL
     1REMAINING--*,F7.2,8X,*GIVEN LIQUID ENTRY--*)
 1003 (ORMAT(*0AVERAGE STRIKING VELOCITY((PS)--*,(8.1,9X,*(UEL TEMPERATU
     1RE(F)--*,F7.2,15X,*PROBABILITY OF LIQUID EXIT--*,F9.6)
 1004 (ORMAT(*0AVERAGE SLANT RANGE((T)--*,(9.1,15X,*(UEL/AIR RATIO--*,
     1F9.6,18X,*PROBABILITY OF VAPOR EXIT--*,F9.6)
 1005 (ORMAT(*0AIRCRA(T ALTITUDE((T)--*,(8.1/*0AIRCRA(T SPEED((PS)--*,
     1F7.1,60X,*PROBABILITY OF VAPOR ENTRY--*,F9.6)
 1006 (ORMAT(*0*,89X,*GIVEN VAPOR ENTRY--*/*0*,93X,*PROBABILITY O( LIQUI
     1D EXIT--*,F9.6/*0*,93X,*PROBABILITY OF VAPOR EXIT--*,F9.6)
 1007 (ORMAT(*-*,49X,*PROBABILITIES O( (UEL TANK DAMAGE*/*0*,60X,*GIVEN
     1A HIT*/*0*,51X,*P(NO EFFECT)             =*,F9.6/*0*,51X,*P(LEAK
     2WITHOUT FIRE)        =*,F9.6/*0*,51X,*P(LEAK AND EXTERNAL FIRE) =*,
     3F9.6/*0*,51X,*P(DESTRUCTIVE RAM)         =*,F9.6/*0*,51X,*P(INTERNA
     4L FIRE/EXPLOSION)=*,F9.6)
 1008 (ORMAT(*0PROBABILITY O( HIT ON (UEL TANK--*,(9.6,7X,*PERCENT (UEL
     1REMAINING--*,F7.2)
 1009 (ORMAT(*0AVERAGE STRIKING VELOCITY((PS)--*,(8.1,9X,*(UEL TEMPERATU
     1RE(F)--*,F7.2)
 1010 (ORMAT(*0AIMING SIGMA((T)--*,(8.1,25X,*(UEL/AIR RATIO--*,(9.6)
 1011 (ORMAT(*0AIRCRA(T ALTITUDE((T)--*,(8.1/*0AIRCRA(T SPEED((PS)--*,
     1F7.1)
```

```
1012 (ORMAT(*0*,49X,*PROBABILITIES O( (UEL TANK DAMAGE*/*0*,60X,*GIVEN
    1A HIT*/*0*,51X,*P(LEAK WITHOUT FIRE)        =*,F9.6/*0*,51X,*P(LEAK
    2AND EXTERNAL FIRE) =*,F9.6/*0*,51X,*P(DESTRUCTIVE RAM)          =*,
    3F9.6/*0*,51X,*P(INTERNAL FIRE/EXPLOSION)=*,F9.6)
1013 (ORMAT(*0TIME INTO MISSION(HRS)--*,(7.3,18X,*THREAT--*,A10)
2000 (ORMAT(2I10,3(10.0)
2001 (ORMAT(10I8)
2002 (ORMAT(2I1,I8,7(10.0)
2003 (ORMAT(5(10.0)
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2005 (ORMAT(4X,6I1,6(10.0)
2006 (ORMAT(5(10.0)
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2008 (ORMAT(8A10)
     END



     SUBROUTINE IN(XT,YT,ZT,LT,WT,HT,PFUEL)
     LOGICAL ENTRY,AFEN
     REAL LT
     COMMON /INOUT/ A,B,C,IASP,JASP,XIN,YIN,ZIN,XOUT,YOUT,ZOUT,ENTRY,
    1AFEN,AFEX,XO,YO,ZO
     IF(C)1,4,2
   1 IASP=5
     ZIN=ZT+HT
     GO TO 3
   2 IASP=6
     ZIN=ZT-HT
   3 YIN=B/C*(ZIN-ZO)+YO
     XIN=A/C*(ZIN-ZO)+XO
     IF(ABS(YIN-YT).GT.WT) GO TO 4
     IF(ABS(XIN-XT).GT.LT) GO TO 4
     GO TO 12
   4 IF(B)5,8,6
   5 IASP=3
     YIN=YT+WT
     GO TO 7
   6 IASP=4
     YIN=YT-WT
   7 ZIN=C/B*(YIN-YO)+ZO
     XIN=A/B*(YIN-YO)+XO
     IF(ABS(ZIN-ZT).GT.HT) GO TO 8
     IF(ABS(XIN-XT).GT.LT) GO TO 8
     GO TO 12
   8 IF(A)9,17,10
   9 IASP=1
     XIN=XT+LT
     GO TO 11
  10 IASP=2
     XIN=XT-LT
  11 ZIN=C/A*(XIN-XO)+ZO
     YIN=B/A*(XIN-XO)+YO
     IF(ABS(ZIN-ZT).GT.HT) RETURN
     IF(ABS(YIN-YT).GT.WT) RETURN
  12 ENTRY=.TRUE.
     IF(PFUEL)17,16,13
  13 IF(PFUEL.EQ.100.0) GO TO 15
     IF(IASP-5)14,16,15
  14 IF(50.0*(ZIN-ZT+HT)/HT.GT.PFUEL) GO TO 16
  15 AFEN=.FALSE.
     RETURN
  16 AFEN=.TRUE.
  17 RETURN
     END
```

```
      SUBROUTINE OUT(XT,YT,ZT,LT,WT,HT,PFUEL)
      LOGICAL AFEX
      REAL LT
      COMMON /INOUT/ A,B,C,IASP,JASP,XIN,YIN,ZIN,XOUT,YOUT,ZOUT,ENTRY,
     1AFEN,AFEX,XO,YO,ZO
      IF(C)1,4,2
    1 JASP=6
      ZOUT=ZT-HT
      GO TO 3
    2 JASP=5
      ZOUT=ZT+HT
    3 YOUT=B/C*(ZOUT-ZO)+YO
      XOUT=A/C*(ZOUT-ZO)+XO
      IF(ABS(YOUT-YT).GT.WT) GO TO 4
      IF(ABS(XOUT-XT).GT.LT) GO TO 4
      GO TO 13
    4 IF(B)5,6,6
    5 JASP=4
      YOUT=YT-WT
      GO TO 7
    6 JASP=3
      YOUT=YT+HT
    7 ZOUT=C/B*(YOUT-YO)+ZO
      XOUT=A/B*(YOUT-YO)+XO
      IF(ABS(ZOUT-ZT).GT.HT) GO TO 8
      IF(ABS(XOUT-XT).GT.LT) GO TO 8
      GO TO 13
    8 IF(A)9,12,10
    9 JASP=2
      XOUT=XT-LT
      GO TO 11
   10 JASP=1
      XOUT=XT+LT
   11 ZOUT=C/A*(XOUT-XO)+ZO
      YOUT=B/A*(XOUT-XO)+YO
      IF(ABS(ZOUT-ZT).GT.HT) GO TO 12
      IF(ABS(YOUT-YT).GT.WT) GO TO 12
      GO TO 13
   12 PRINT 1000
      STOP
   13 IF(PFUEL.EQ.0.0) GO TO 15
      IF(PFUEL.EQ.100.0) GO TO 14
      IF(JASP.EQ.6) GO TO 14
      IF(50.0*(ZOUT-ZT+HT)/HT.GT.PFUEL) GO TO 15
   14 AFEX=.FALSE.
      RETURN
   15 AFEX=.TRUE.
      RETURN
 1000 FORMAT(* ENTRY BUT NO EXIT*)
      END
      FUNCTION DEMACH(AMACH,HT)
      IF(HT.LT.36089.0) GO TO 1
      DEMACH=968.452*AMACH
      RETURN
    1 DEMACH=49.040772*SQRT(518.688-0.00356616*HT)*AMACH
      RETURN
      END
```

```
      SUBROUTINE REPT1
      COMMON /PROFILE/ HT(250),VT(250),FAR(250,10),FLEFT(250,10),
     1FTEMP(250,10),GAL(10),NTANKS,NTP,TINC
      COMMON /ALPHA/ ATANK(2,10),AWEAP(32),AWAR(2),ASOL(2),ATARG
      INTEGER GAL
      READ(6)(HT(I),I=1,8013)
      READ 2000,((ATANK(I,J),I=1,2),J=1,NTANKS),ATARG
      NLEFT=NTANKS
      IST=1
    1 IEND=IST+4
      NLEFT=NLEFT-5
      IF(NLEFT.GT.0) GO TO 2
      IEND=IEND+NLEFT
    2 LINE=0
      NTPS=1
    3 IF(MOD(LINE,60).GT.0) GO TO 4
      PRINT 1000,ATARG,((ATANK(J,I),J=1,2),I=IST,IEND)
      PRINT 1001,(GAL(I),I=IST,IEND)
      PRINT 1002
      LINE=LINE+12
    4 TIM=TINC*(NTPS-1)
      PRINT 1003,TIM,(FAR(NTPS,I),FLEFT(NTPS,I),I=IST,IEND)
      LINE=LINE+1
      NTPS=NTPS+1
      IF(NTPS.LE.NTP) GO TO 3
      IF(NLEFT.LE.0) RETURN
      IST=IEND+1
      GO TO 1
 1000 FORMAT(*1*,51X,*FUEL TANK VULNERABILITY MODEL*/62X,*REPORT 1*//
     158X,*VEHICLE--*,A10/11X,5(4X,2A10))
 1001 FORMAT(11X,5(3X,21(*-*))/11X,5(I8,* GALLON CAPACITY*))
 1002 FORMAT(11X,5(3X,21(*-*))/*  TIME INTO*,5(15X,*PCT. FUEL*)/
     1*   MISSION *,5(*    F/A RATIO    REMAINING*))
 1003 FORMAT(1X,F10.3,5(F12.6,F12.2))
 2000 FORMAT(5A10)
      END
```

```
        FUNCTION GAUS(SIGMA)
        GAUS=0.0
        DO 1 I=1,12
      1 GAUS=GAUS+RANF(0.0)
        GAUS=SIGMA*(GAUS-6.0)
        RETURN
        END
    9  END OF RECORD
```

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